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# Measurement of the cross-section and charge asymmetry of $W$ bosons produced in proton–proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

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**Abstract** This paper presents measurements of the  $W^+ \rightarrow \mu^+ \nu$  and  $W^- \rightarrow \mu^- \bar{\nu}$  cross-sections and the associated charge asymmetry as a function of the absolute pseudorapidity of the decay muon. The data were collected in proton–proton collisions at a centre-of-mass energy of 8 TeV with the ATLAS experiment at the LHC and correspond to a total integrated luminosity of  $20.2 \text{ fb}^{-1}$ . The precision of the cross-section measurements varies between 0.8 and 1.5% as a function of the pseudorapidity, excluding the 1.9% uncertainty on the integrated luminosity. The charge asymmetry is measured with an uncertainty between 0.002 and 0.003. The results are compared with predictions based on next-to-next-to-leading-order calculations with various parton distribution functions and have the sensitivity to discriminate between them.

## 1 Introduction

Measurements of the  $W^+$  and  $W^-$  boson cross-sections in hadron collisions are a sensitive probe of quantum chromodynamics (QCD). High-precision predictions at next-to-next-to-leading-order (NNLO) accuracy in QCD are available to compare with data. Of particular interest is the ability of such measurements to discriminate between different parton distribution functions (PDFs) [1–7], because the  $W$  boson rapidity<sup>1</sup>  $y$  is strongly correlated with the initial-state parton

momentum fractions  $x$ . In high-energy proton–proton collisions, the main production mechanism of single  $W$  bosons is a valence quark annihilating with a sea antiquark. The  $W$  bosons are preferentially produced with a boost in the direction of the incoming valence quark, as the quark is more likely to be at a higher  $x$  than the corresponding antiquark. Since the PDFs of  $u$  and  $d$  quarks in the proton differ (largely due to there being two valence  $u$  quarks and one valence  $d$  quark), there is a production asymmetry between  $W^+$  and  $W^-$  bosons (referred to in this paper as the  $W$  boson charge asymmetry), which also varies as a function of rapidity. The boson rapidity cannot be determined unambiguously in leptonic decays of the  $W$  boson because the decay neutrino passes through the detector unobserved. The charge asymmetry can instead be measured as a function of the decay lepton's pseudorapidity  $\eta_\ell$ , which is strongly correlated with the  $W$  boson rapidity.

The  $W$  boson charge asymmetry was measured in proton–antiproton collisions by the CDF and D0 collaborations [8–10]. It was also measured, along with the individual cross-sections, in proton–proton collisions at the LHC by the ATLAS Collaboration at centre-of-mass energies of  $\sqrt{s} = 5$  TeV [11] and 7 TeV [2], by the CMS Collaboration at  $\sqrt{s} = 7$  and 8 TeV [12–14], and by the LHCb Collaboration at  $\sqrt{s} = 7$  and 8 TeV [15–17].

This paper presents measurements of the integrated fiducial cross-sections for  $W^+ \rightarrow \mu^+ \nu$  and  $W^- \rightarrow \mu^- \bar{\nu}$ , as well as the differential cross-sections,  $d\sigma_{W^+}/d\eta_\mu$  and  $d\sigma_{W^-}/d\eta_\mu$ , as a function of  $|\eta_\mu|$ , where  $\eta_\mu$  is the pseudorapidity of the decay muon. The data used were collected in proton–proton collisions at a centre-of-mass energy of  $\sqrt{s} = 8$  TeV with the ATLAS experiment at the LHC and correspond to a total integrated luminosity of  $20.2 \text{ fb}^{-1}$  [18]. The muon decay channel ( $W \rightarrow \mu \nu$ ) is particularly well suited for this measurement due to good lepton identification and small contributions from background processes. In addition, a measurement of the  $W$  boson charge asymmetry  $A_\mu$  is presented, also as a function of  $|\eta_\mu|$ . The asymmetry is defined

<sup>1</sup> ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the centre of the detector and the  $z$ -axis coinciding with the axis of the beam pipe. The  $x$ -axis points from the interaction point to the centre of the LHC ring, and the  $y$ -axis points upward. Polar coordinates  $(r, \phi)$  are used in the transverse plane,  $\phi$  being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle  $\theta$  as  $\eta = -\ln \tan(\theta/2)$ . The rapidity  $y$  of a system is defined in terms of its energy  $E$  and its longitudinal momentum  $p_z$  as  $y = (1/2) \ln[(E + p_z)/(E - p_z)]$ . Angular separations between particles or reconstructed objects are measured in  $\eta$ – $\phi$  space using  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ .

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in terms of the  $W^+$  and  $W^-$  differential cross-sections as

$$A_\mu = \frac{d\sigma_{W_{\mu^+}}/d\eta_\mu - d\sigma_{W_{\mu^-}}/d\eta_\mu}{d\sigma_{W_{\mu^+}}/d\eta_\mu + d\sigma_{W_{\mu^-}}/d\eta_\mu}. \quad (1)$$

The measurements are performed in a fiducial phase space, which is defined by the kinematics and geometrical acceptance of the muon. All measurements are compared with predictions from a calculation performed at NNLO accuracy using the DYNNLO program [19]. The DYNNLO predictions are produced with six different PDF sets.

## 2 The ATLAS detector

The ATLAS detector [20] at the LHC covers nearly the entire solid angle around the collision point. It consists of an inner tracking detector (ID) surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer (MS) incorporating three large superconducting toroid magnets. The ID is immersed in a 2 T axial magnetic field and provides charged-particle tracking in the range  $|\eta| < 2.5$ . A high-granularity silicon pixel detector typically provides three measurements per track and is followed by a silicon microstrip tracker, which usually provides four three-dimensional measurement points per track. These silicon detectors are complemented by a transition radiation tracker, which enables radially extended track reconstruction up to  $|\eta| = 2.0$ .

The calorimeter system covers the pseudorapidity range  $|\eta| < 4.9$ . Electromagnetic calorimetry is provided by barrel and endcap high-granularity lead/liquid-argon (LAr) sampling calorimeters in the  $|\eta| < 3.2$  region. A thin LAr pre-sampler, covering  $|\eta| < 1.8$ , corrects for energy loss in the material upstream of the calorimeters. Hadronic calorimetry is provided in the  $|\eta| < 1.7$  region by the steel/scintillator tile calorimeter, segmented into three barrel structures, and in the endcap region by two copper/LAr calorimeters. The forward regions  $3.1 < |\eta| < 4.9$  are covered by copper/LAr and tungsten/LAr calorimeter modules optimised for electromagnetic and hadronic measurements, respectively.

The MS has separate trigger and precision tracking chambers measuring the deflection of muons in a magnetic field generated by superconducting air-core toroids. The precision chamber system covers the region  $|\eta| < 2.7$  with three layers of monitored drift tubes, complemented by cathode-strip chambers in the forward regions  $2.0 < |\eta| < 2.7$ , where the background is highest. There is a transition between the barrel and endcap muon detectors around  $|\eta| = 1.05$ . The muon trigger system covers the range of  $|\eta| < 2.4$  with resistive-plate chambers in the barrel and thin-gap chambers in the endcap regions.

A three-level trigger system [21,22] selected candidate events in 2012. The level-1 trigger was implemented in hardware and used a subset of detector information to reduce the event rate to a design value of at most 75 kHz. This was followed by two software-based trigger levels which together reduced the event rate to about 400 Hz.

## 3 Analysis methodology

### 3.1 Description of the measurements

The integrated cross-sections for  $W^+ \rightarrow \mu^+ \nu$  and  $W^- \rightarrow \mu^- \bar{\nu}$  production are measured in a fiducial phase space defined at the particle level by requiring the muon transverse momentum  $p_T^\mu$  to be greater than 25 GeV and the neutrino transverse momentum  $p_T^\nu$  to be greater than 25 GeV. The absolute muon pseudorapidity is required to be less than 2.4. The  $W$  boson transverse mass is

$$m_T = \sqrt{2p_T^\mu p_T^\nu (1 - \cos(\phi^\mu - \phi^\nu))}, \quad (2)$$

where  $\phi^\mu$  and  $\phi^\nu$  are the azimuthal angles of the muon and neutrino, respectively. For this analysis,  $m_T$  must be at least 40 GeV, both at reconstruction and particle level. The requirements on fiducial quantities are defined before the emission of final-state photon radiation (i.e. at the ‘Born level’).

The differential cross-sections and charge asymmetry are measured in the same fiducial phase space as for the integrated measurement. These are measured in 11 bins of absolute muon pseudorapidity between 0 and 2.4 with bin edges at 0, 0.21, 0.42, 0.63, 0.84, 1.05, 1.37, 1.52, 1.74, 1.95, 2.18, and 2.4. The bin edges are identical to those used in the ATLAS 7 TeV measurement [2].

### 3.2 Data and simulated event samples

The data for this analysis comprise the entire ATLAS  $\sqrt{s} = 8$  TeV data set recorded between April and December 2012, corresponding to an integrated luminosity of  $20.2 \text{ fb}^{-1}$ . The average number of proton–proton interactions per bunch crossing  $\langle \mu \rangle$  was 20.7. Only events recorded with stable beams and the detector operating well are selected. The relative uncertainty of the LHC proton beam energy of  $\pm 0.1\%$  [23] has no significant effect on the results.

Events from Monte Carlo (MC) simulations, including simulation of the ATLAS detector, are used for the background estimation and to correct the measured data for detector acceptance, efficiency, and resolution effects.

The  $W \rightarrow \mu \nu$  signal process was simulated using POWHEG-BOX [24,25] at next-to-leading order (NLO) in perturbative QCD using the CT10 set of PDFs [26] and interfaced to PYTHIA 8.170 [27] with the AU2 set of tuned

parameters [28] to simulate the parton shower, hadronisation, and underlying event and to PHOTOS [29] to simulate final-state photon radiation (FSR). This is referred to as POWHEG+PYTHIA8 in this paper. An alternative signal sample was simulated using NLO SHERPA 1.4 [30] and the CT10 PDF set to cross-check the results obtained using POWHEG+PYTHIA8 and to evaluate systematic uncertainties in the signal modelling.

POWHEG+PYTHIA8 with the CT10 PDF set was used to simulate the background processes  $W \rightarrow \tau\nu$  and  $Z \rightarrow \mu\mu$  (with the AU2 tune set) and POWHEG+PYTHIA6 [31,32] also with the CT10 PDF set was used to simulate the  $t\bar{t}$  process (with the P2011C tune set [33]). The  $Z \rightarrow \tau\tau$  process was simulated using ALPGEN [34] with the CTEQ6L1 PDF set [35] interfaced to Herwig [36] to simulate the parton shower and JIMMY [37] to model the underlying event. The single-top process in the  $s$ -channel and  $Wt$ -channels was simulated with MC@NLO [38] interfaced to JIMMY. The  $t$ -channel was generated with ACERMC [39] interfaced to PYTHIA. The backgrounds from the diboson processes  $WW$ ,  $WZ$ , and  $ZZ$  were simulated using Herwig at leading order with the CTEQ6L1 PDF set. In all cases, the GEANT4 [40] program was used to simulate the passage of particles through the ATLAS detector [41]. The multijet background is estimated using a data-driven technique, described in Sect. 3.4. A  $b\bar{b} \rightarrow \mu X$  MC sample, simulated using PYTHIA8 with the AU2 tune set, is used to cross-check the data-driven estimation.

Differences in reconstruction, trigger, and isolation efficiencies for muons between MC simulations and data are evaluated using a tag-and-probe method [42] and are corrected by reweighting the MC simulated events. The muon reconstruction efficiencies are parameterised versus  $\eta$  and  $\phi$ , the muon isolation efficiencies versus  $\eta$  and transverse momentum  $p_T$ , and the muon trigger efficiencies versus  $\eta$ ,  $\phi$ , and  $p_T$ . The reconstruction, trigger and isolation efficiencies are evaluated separately for positive and negative muons. This separate evaluation is particularly necessary in the case of the trigger efficiencies, which differ by up to 3% (depending on  $\eta$ ) between positive and negative muons, much greater than the total uncertainty in the cross-section from other sources. Corrections are also applied to MC events for the description of the muon momentum scales and resolution, which are determined from fits to the observed mass distributions of  $Z \rightarrow \mu\mu$  candidates in data and MC simulations [42]. To correct for charge-dependent biases of the muon momentum scale due to residual misalignments in the ID and MS, an additional momentum-dependent correction parameterised versus  $\eta$  and  $\phi$  is applied. An associated uncertainty corresponding to the full size of the correction is included.

All simulated samples are normalised using their respective inclusive cross-sections at higher orders in perturbative

QCD. The  $W$  and  $Z$  predictions are scaled to the NNLO calculation obtained with DYNLO v1.5 [19,43] and the MSTW2008 PDF set [44]. The production of top quarks is normalised using the prediction at NNLO+NNLL precision from the Top++2.0 program for  $t\bar{t}$  [45–51], to the calculations in Refs. [52–54] for single top quarks, and for diboson production to the NLO calculations following the procedure described in Ref. [55].

The effect of multiple interactions per bunch crossing (pile-up) is simulated by overlaying minimum-bias MC events generated with PYTHIA8 (with the A2 tune set) [41]. The simulated event samples are reweighted to describe the distribution of the number of pile-up events in the data. The MC simulations are also reweighted to better describe the distribution of the longitudinal position of the primary proton–proton collision vertex [56] in data.

### 3.3 Event selection

Candidate  $W \rightarrow \mu\nu$  events are selected with the requirement that at least one of two single-muon triggers are satisfied. A high-threshold trigger requires muons to have  $p_T > 36$  GeV, whilst a low-threshold trigger requires  $p_T > 24$  GeV alongside the requirement that the muon must be isolated from additional nearby tracks.

Muon candidates are reconstructed by combining tracks measured in both the ID and the MS [42]. The  $p_T$  of the ID track is required to be greater than 25 GeV and the absolute pseudorapidity to be less than 2.4. Track quality requirements are imposed for muon identification and background suppression. The transverse impact parameter significance is required to be less than 3 to ensure that the muon candidates originate from a primary proton–proton interaction vertex. The muon candidates are also required to be isolated, satisfying  $I_\mu < 0.1$ , where  $I_\mu$  is the scalar sum of the  $p_T$  of tracks within a cone of size  $\Delta R = 0.4$  around the muon (excluding the muon track) divided by the  $p_T$  of the muon. Events are required to contain exactly one muon candidate satisfying the above criteria.

To reduce background contamination, in particular from multijet processes, events are required to have missing transverse momentum  $E_T^{\text{miss}}$  greater than 25 GeV. The  $E_T^{\text{miss}}$  is reconstructed using energy depositions in the calorimeters and tracks reconstructed in the inner detector and muon spectrometer [57]. It is defined as the absolute value of the negative of the vectorial sum of the transverse momenta of reconstructed objects (e.g. electrons, muons, jets) and tracks not associated with these objects. These are labelled the hard and soft terms, respectively.

The  $W$  boson transverse mass  $m_T$  is required to be larger than 40 GeV. This variable is defined analogously to Eq. (2) with  $p_T^\nu$  replaced by  $E_T^{\text{miss}}$  and  $\phi^\nu$  replaced by the azimuthal angle related to the  $E_T^{\text{miss}}$ .

### 3.4 Estimation of backgrounds

The backgrounds from all sources other than multijet processes are estimated using the MC samples detailed in Sect. 3.2. The  $Z \rightarrow \mu\mu$  process with one of the muons not identified contributes between 1% and 8% of selected data events, depending on the value of  $|\eta_\mu|$ . This is the largest background for  $|\eta_\mu| \gtrsim 1.4$ . The contribution from  $W \rightarrow \tau\nu$  where the  $\tau$ -lepton decays into a muon is 2% of the selected data events and approximately constant as a function of  $|\eta_\mu|$ . The backgrounds from  $Z \rightarrow \tau\tau$ ,  $t\bar{t}$ , and the diboson processes  $WW$ ,  $WZ$ , and  $ZZ$  each amount to less than 0.3% of the selected data.

Multijet processes contribute between 2% and 4% of the selected data and are the largest sources of background for  $|\eta_\mu| \lesssim 1.4$ . The number and properties of the background events arising from multijet processes are estimated using a data-driven template-fit technique, similar to that used in Ref. [58]. A multijet-dominated sample is obtained from data by selecting events passing the nominal selection except that the muon fails the isolation criterion. For this purpose, events satisfying a trigger without an isolation requirement are used. Multijet templates are constructed from this sample, in a series of mutually exclusive slices in muon isolation, for each distribution of interest. The residual contribution from signal and other background sources, estimated from MC simulations, is subtracted. The normalisations of the multijet templates in the signal region are obtained by fitting the templates to data in three discriminating variables:  $E_T^{\text{miss}}$ ,  $m_T$ , and the ratio  $p_T^\mu/m_T$ . The fits are performed in two phase-space regions (fitting regions) in which the selections on  $E_T^{\text{miss}}$  and  $m_T$  are relaxed in order to enrich the multijet background contribution. A requirement that the  $W$  transverse momentum be less than 30 GeV is introduced in one fitting region to remove a region poorly modelled by signal MC simulations. The normalisation of the multijet template is allowed to float in each of the fits and the total MC-based signal plus background is kept constant. The multijet normalisation in the signal selection is extracted using each discriminating variable in both fitting regions (a total of six estimates). It is assumed that the normalisations of the templates in the fitting regions are the same as for the signal selection. The fits described above are performed for each muon-isolation slice (i.e. six fits per slice). The normalisation estimate extracted in each muon-isolation slice (for a particular discriminating variable and fitting region) is used to linearly extrapolate to an isolation value of 0.05, which is the average isolation of multijet events in the signal region as estimated using the  $b\bar{b} \rightarrow \mu X$  MC simulation.

The central value of the multijet background is chosen to be the average of the extrapolated curves at  $I_\mu = 0.05$ , and the spread gives one component of the systematic uncertainty, which is estimated to be bin-to-bin correlated and 50%

**Table 1** The number of data events after event selection for  $W^+ \rightarrow \mu^+\nu$  and  $W^- \rightarrow \mu^-\bar{\nu}$  and the percentage of selected data that each of the three major backgrounds constitutes

	$W^+ \rightarrow \mu^+\nu$	$W^- \rightarrow \mu^-\bar{\nu}$
Number of events	50 390 184	34 877 365
Percentage of data		
Multijet	$2.4 \pm 0.3$	$3.1 \pm 0.3$
$W \rightarrow \tau\nu$	$1.9 \pm 0.1$	$2.0 \pm 0.1$
$Z \rightarrow \mu\mu$	$3.1 \pm 0.2$	$4.0 \pm 0.2$
Others	$0.62 \pm 0.02$	$0.82 \pm 0.03$

charge correlated. This uncertainty component includes the effects from the choice of the discriminating variable and the definition of the fitting regions. Another component arises from the effect of the cross-section uncertainty on the signal simulation contribution in the fitting regions ( $\pm 5\%$ ). The fit is repeated varying this and the deviation from the nominal normalisation is taken as an uncertainty, which is again treated as being charge and bin-to-bin correlated. The fit also has a statistical uncertainty, which is treated as being uncorrelated between charges and bins. This is largely due to the limited number of data events for the multijet templates passing the signal selection in each muon-isolation slice. The size of the multijet systematic uncertainty is reported in Sect. 4. The above procedure is performed separately in each bin of muon pseudorapidity. A summary of the most important backgrounds including systematic uncertainties is given in Table 1.

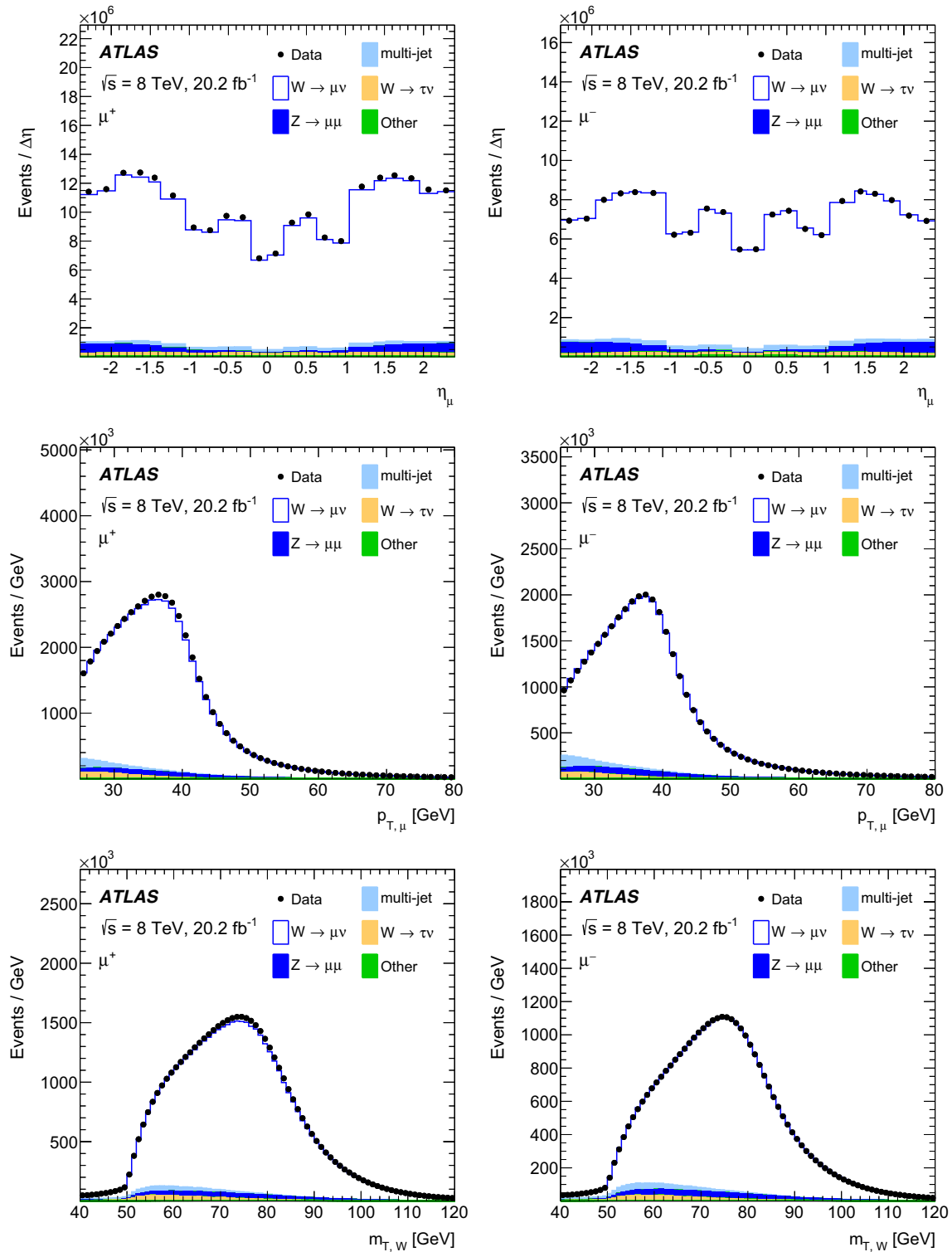
Figure 1 shows the muon  $\eta$ , muon  $p_T$ , and  $W$  transverse mass distributions of selected events with positive muons (left) and with negative muons (right). The data are compared with the sum of MC and data-based estimates for the signal and the backgrounds. The predictions are normalised to the luminosity of the data, after first normalising each MC cross-section to a corresponding higher-order prediction. A normalisation shift between data and MC simulations of approximately 1% is observed for the positive muon plots. This is covered by the uncertainty in the MC signal prediction due to the cross-section uncertainty. Otherwise, the combined prediction describes the data well and within the uncertainties.

### 3.5 Obtaining the fiducial cross-sections

The fiducial  $W^\pm$  differential cross-sections in bin  $i$  of pseudorapidity  $(d\sigma_{W^\pm}/d\eta_\mu)_i$  are obtained from

$$\left(\frac{d\sigma_{W^\pm}}{d\eta_\mu}\right)_i = \frac{N_{\text{data},i} - N_{\text{bkg},i}}{\Delta\eta_i \cdot C_{W^\pm,i} \cdot \int \mathcal{L} dt},$$





**Fig. 1** The muon  $\eta$  (top), muon  $p_T$  (centre), and  $W$  boson transverse mass (bottom) distributions of selected events with positive muons (left) and negative muons (right). The statistical uncertainties of the data points are smaller than the size of the markers

where  $N_{\text{data},i}$  is the number of selected candidate events in data,  $N_{\text{bkg},i}$  is the number of background events estimated using the methods described in Sect. 3.4,  $\Delta\eta_i$  is the width

of bin  $i$ , and  $\int \mathcal{L} dt$  is the integrated luminosity. The results are provided as a function of absolute pseudorapidity, where  $\Delta|\eta_i| = 2 \cdot \Delta\eta_i$ . The term  $C_{W^\pm,i}$  is a factor (different for

**Table 2** The  $C_{W^\pm,i}$  values with their associated systematic uncertainties as a function of  $|\eta_\mu|$  and the integrated global correction factor  $C_{W^\pm}$ , each for  $W^+$  and  $W^-$

$ \eta_\mu $	$W^+ \rightarrow \mu^+ \nu$	$W^- \rightarrow \mu^- \bar{\nu}$
0.00–0.21	$0.508 \pm 0.004$	$0.505 \pm 0.004$
0.21–0.42	$0.684 \pm 0.004$	$0.679 \pm 0.004$
0.42–0.63	$0.702 \pm 0.005$	$0.702 \pm 0.005$
0.63–0.84	$0.611 \pm 0.004$	$0.613 \pm 0.005$
0.84–1.05	$0.603 \pm 0.004$	$0.601 \pm 0.005$
1.05–1.37	$0.795 \pm 0.006$	$0.796 \pm 0.007$
1.37–1.52	$0.848 \pm 0.008$	$0.845 \pm 0.007$
1.52–1.74	$0.861 \pm 0.009$	$0.856 \pm 0.007$
1.74–1.95	$0.856 \pm 0.009$	$0.855 \pm 0.008$
1.95–2.18	$0.792 \pm 0.008$	$0.794 \pm 0.009$
2.18–2.40	$0.802 \pm 0.008$	$0.812 \pm 0.011$
Integrated	$0.736 \pm 0.003$	$0.727 \pm 0.003$

positive and negative channels) which corrects for the various detector inefficiencies and resolution effects. This is estimated using  $W \rightarrow \mu\nu$  signal MC simulations and defined for each bin  $i$  as the number of reconstructed events satisfying the same selection criteria as data divided by the number of generated events in the fiducial phase space. The charge asymmetry is then evaluated in each absolute pseudorapidity bin using Eq. (1). A bin-by-bin correction method is used as the purity of each bin is 99% or larger, where the bin purity is defined as the ratio of events generated and reconstructed in a certain bin to all events reconstructed in that bin (where all events are in the generator-level fiducial phase space).

The integrated fiducial cross-sections ( $\sigma_{W^\pm}$ ) are obtained using one global correction factor,  $C_{W^\pm}$ , (i.e. the total number of reconstructed events satisfying the same selection criteria as data divided by the total number of generated events in the integrated fiducial phase space). The values are also obtained by summing the differential cross-sections as a function of

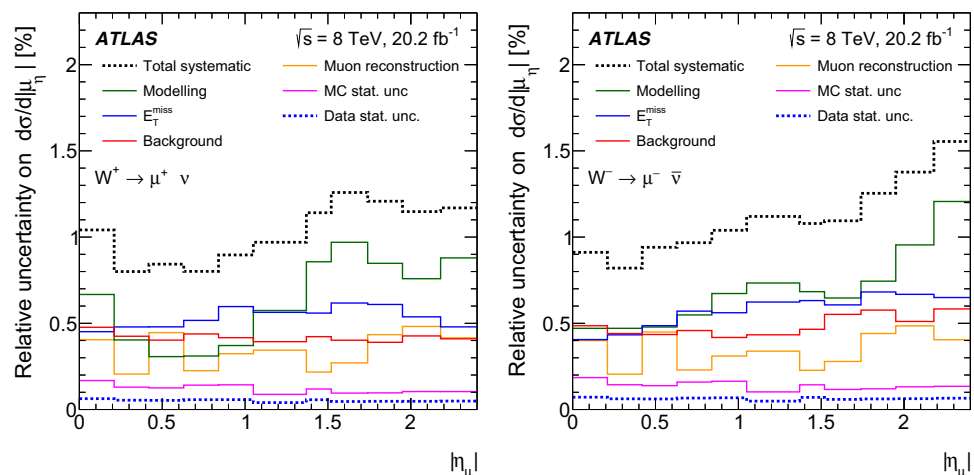
$|\eta_\mu|$ , and the results are consistent. Table 2 lists the  $C_{W^\pm,i}$  values with their associated systematic uncertainties as a function of  $|\eta_\mu|$  and gives the integrated global correction factor  $C_{W^\pm}$ , each for  $W^+$  and  $W^-$ .

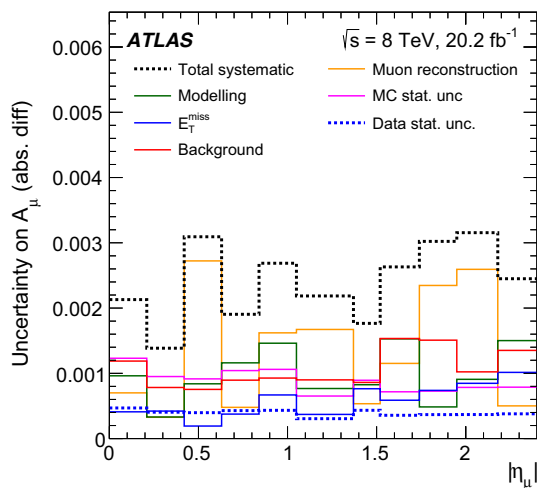
#### 4 Systematic uncertainties

This section describes the sources of systematic uncertainty considered for the cross-section and the asymmetry measurements. The size of these uncertainties as a function of  $|\eta_\mu|$  is provided in Figs. 2 and 3. The data statistical uncertainties are also shown and are small compared with the total systematic uncertainty. Table 3 lists the  $W^+ \rightarrow \mu^+ \nu$  and  $W^- \rightarrow \mu^- \bar{\nu}$  cross-sections and the asymmetry as a function of the absolute pseudorapidity of the muon, along with the data statistical uncertainties and dominant systematic uncertainties. Most sources of systematic uncertainty, described below, are treated as being correlated between the positive and negative muon channels unless otherwise noted, and therefore their relative impact is reduced for the asymmetry measurement.

Experimental sources of uncertainty are possible mis-modelling of the muon momentum scale, resolution, or charge-dependent sagitta bias as well as of the reconstruction, trigger, and isolation efficiencies. Such uncertainties form a small but non-negligible fraction of the total uncertainty, 0.5% or less of the differential cross-section. A test is performed to check the compatibility of the cross-sections measured separately in positive and negative muon pseudorapidity; this is an important cross-check of the correction procedure as the detector is not forward-backward symmetric with respect to the trajectory of a charged particle. A further small uncertainty (up to 0.4% depending on the  $|\eta_\mu|$  bin) is added to cover the small differences observed. This uncertainty is treated as being uncorrelated between charges and propagated to the asymmetry measurement. The above uncertainties are combined in the column labelled ‘Muon

**Fig. 2** The relative systematic uncertainty from each source for the  $W^+$  (left) and  $W^-$  (right) differential cross-sections as a percentage of the differential cross-section. Also shown are the total systematic and statistical uncertainties





**Fig. 3** The systematic uncertainty from each source for the  $W$  boson charge asymmetry as an absolute difference from the central value. Also shown are the total systematic and statistical uncertainties

Reconstruction' in Table 3. Additional sources of uncertainty are the mis-modelling of the pile-up event activity and of the primary vertex longitudinal position, both of which are small.

Uncertainties from the mis-modelling of the missing transverse momentum also contribute substantially to the total systematic uncertainty in the cross-section, although they are reduced for the asymmetry measurements. These include mis-modelling in the jet energy scale and resolution, as well as of the momentum balance between the soft term and the total transverse momentum of the hard objects in  $Z \rightarrow \mu\mu$  calibration events [57]. The muon-related uncertainties in the missing transverse momentum are treated as being fully correlated with those of the signal muon and are part of the muon systematic uncertainties. The sum of all soft-term uncertainties is the largest or second largest contributor (depending on the  $|\eta_\mu|$  bin) to the total uncertainty in the differential cross-sections but is significantly less important for the asymmetry measurement. The hard-term uncertainties are small for both the cross-section and asymmetry measurements. The soft-term and hard-term uncertainties are assumed to be uncorrelated with each other.

Uncertainties due to the mis-modelling of the background processes are also considered. For the backgrounds modelled with MC simulations, these are estimated by varying their normalisation within theoretical uncertainties and observing the effect on the final measurements. The cross-section uncertainty for the  $Z \rightarrow \mu\mu$  process and the  $W \rightarrow \tau\nu$  process is 5% [59]. The cross-section uncertainty for  $t\bar{t}$  production is 6% [45–51], and for single top production 7% [52–54]. The cross-section uncertainty for diboson production is 5% for  $WW$  and  $ZZ$  production and 7% for  $WZ$  production [55].

As mentioned in Sect. 3.4, there are three components of the uncertainty in the multijet background normalisation. The

two correlated uncertainties are larger for the cross-section measurements (totalling around 0.5%), whilst the effect of the statistical component is larger for the asymmetry measurement.

The statistical uncertainty due to the limited number of MC events for the other backgrounds and for the signal process is small for the cross-section measurement (less than 0.2%) but becomes significant for the asymmetry measurement (around one third of the total uncertainty), as it is completely uncorrelated between positive and negative channels.

Theoretical sources of uncertainty arise from the choice of PDF interfaced to the POWHEG+PYTHIA8 signal MC simulations (the CT10 PDF set). This uncertainty is estimated by reweighting the POWHEG+PYTHIA8 events to the nominal values of the CT14 [1] and MSTW2008nlo68cl [44] PDF sets using the LHAPDF interface [60], taking the difference to the nominal values and adding in quadrature. The PDF uncertainty is small for both the fiducial cross-section and asymmetry measurements.

The alternative SHERPA signal sample is used to estimate an uncertainty from POWHEG+PYTHIA8 related to the modelling of the matrix elements that impact kinematics, as well as the underlying event activity and hadronisation (which affects the  $E_T^{\text{miss}}$  measurement). The difference between the dressed-level  $C_W$  values obtained using the POWHEG+PYTHIA8 and SHERPA simulations is statistically significant and assigned as a systematic uncertainty. This is labelled as 'Modelling' in Table 3. The dressed-level is defined by combining the four-momentum of each muon after photon FSR with that of photons radiated within a cone defined by  $\Delta R = 0.1$  around the muon. This is one of the largest systematic uncertainties for both the cross-section (up to 1% at large  $|\eta_\mu|$ ) and the asymmetry measurements. The uncertainty in the luminosity is 1.9% [18]. For the asymmetry, the uncertainty in the luminosity only affects the asymmetry measurement through negligible effects in the background estimation, and it is therefore considered fully correlated between the  $W^+$  and  $W^-$  samples.

## 5 Theoretical predictions

The  $W^+$  and  $W^-$  integrated and differential cross-sections and the  $W$  boson charge asymmetry are compared with theoretical predictions from an optimised version of the DYNLO generator [19], which simulates initial-state QCD corrections to NNLO accuracy at leading order in the electroweak couplings with parameters set according to the  $G_\mu$  scheme [61]. The input parameters (the Fermi constant  $G_F$ , the masses and widths of the  $W$  and  $Z$  bosons, and the CKM matrix elements) are taken from Ref. [62]. The DYNLO predictions are calculated with the PDF sets from CT14 NNLO [1], ATLASepWZ2016 [2],



**Table 3** Cross-sections (differential in  $\eta_\mu$ ) and asymmetry, as a function of  $|\eta_\mu|$ . The central values are provided along with the statistical and dominant systematic uncertainties: the data statistical uncertainty (Data Stat.), the  $E_T^{\text{miss}}$  uncertainty, the uncertainties related to muon reconstruction (Muon Reco.), those related to the background, those from MC statistics (MC Stat.), and modelling uncertainties. The uncertainties of the cross-sections are given in percent and those of the asymmetry as an absolute difference from the nominal

$ \eta_\mu $	Data stat.		$E_{\text{T}}^{\text{miss}}$	Muon reco.	Background	MC stat.	Modelling
$d\sigma_{W_{\mu^+}}/d\eta_\mu$ [pb]							
0.00–0.21	630.3	0.06	0.45	0.40	0.48	0.17	0.67
0.21–0.42	635.2	0.05	0.48	0.21	0.42	0.13	0.40
0.42–0.63	641.6	0.05	0.48	0.45	0.40	0.13	0.31
0.63–0.84	638.1	0.06	0.52	0.23	0.44	0.14	0.31
0.84–1.05	642.8	0.06	0.60	0.32	0.42	0.14	0.37
1.05–1.37	654.7	0.04	0.56	0.34	0.39	0.09	0.57
1.37–1.52	661.0	0.06	0.56	0.22	0.42	0.12	0.86
1.52–1.74	662.3	0.05	0.62	0.27	0.40	0.10	0.97
1.74–1.95	661.8	0.05	0.61	0.43	0.39	0.10	0.85
1.95–2.18	657.5	0.05	0.54	0.48	0.43	0.10	0.76
2.18–2.40	641.5	0.05	0.48	0.42	0.41	0.10	0.88
$d\sigma_{W_{\mu^-}}/d\eta_\mu$ [pb]							
0.00–0.21	493.7	0.07	0.41	0.40	0.49	0.18	0.47
0.21–0.42	489.6	0.06	0.43	0.20	0.44	0.14	0.47
0.42–0.63	485.8	0.06	0.49	0.45	0.43	0.14	0.48
0.63–0.84	474.3	0.07	0.57	0.23	0.46	0.16	0.55
0.84–1.05	465.0	0.07	0.56	0.31	0.42	0.16	0.67
1.05–1.37	455.7	0.05	0.62	0.34	0.43	0.10	0.73
1.37–1.52	439.7	0.07	0.63	0.23	0.47	0.14	0.68
1.52–1.74	427.3	0.06	0.61	0.28	0.55	0.12	0.65
1.74–1.95	410.2	0.06	0.68	0.44	0.58	0.12	0.74
1.95–2.18	389.1	0.06	0.67	0.49	0.51	0.13	0.95
2.18–2.40	368.3	0.07	0.65	0.40	0.58	0.13	1.21
$A_\mu$							
0.00–0.21	0.1215	0.0005	0.0004	0.0007	0.0012	0.0012	0.0010
0.21–0.42	0.1294	0.0004	0.0004	0.0003	0.0008	0.0010	0.0003
0.42–0.63	0.1383	0.0004	0.0002	0.0027	0.0008	0.0009	0.0008
0.63–0.84	0.1473	0.0004	0.0004	0.0005	0.0009	0.0010	0.0012
0.84–1.05	0.1605	0.0004	0.0007	0.0016	0.0009	0.0011	0.0015
1.05–1.37	0.1792	0.0003	0.0004	0.0017	0.0009	0.0007	0.0008
1.37–1.52	0.2011	0.0004	0.0008	0.0005	0.0009	0.0009	0.0008
1.52–1.74	0.2156	0.0004	0.0006	0.0012	0.0015	0.0007	0.0015
1.74–1.95	0.2347	0.0004	0.0007	0.0023	0.0015	0.0007	0.0005
1.95–2.18	0.2565	0.0004	0.0008	0.0026	0.0010	0.0008	0.0009
2.18–2.40	0.2706	0.0004	0.0010	0.0005	0.0014	0.0008	0.0015

HERAPDF2.0 [3], NNPDF3.1 [4], PDF4LHC15 [5] and MMHT2014 NNLO [6]. The renormalisation and factorisation scales are set equal to the invariant mass of the muon–neutrino pair.

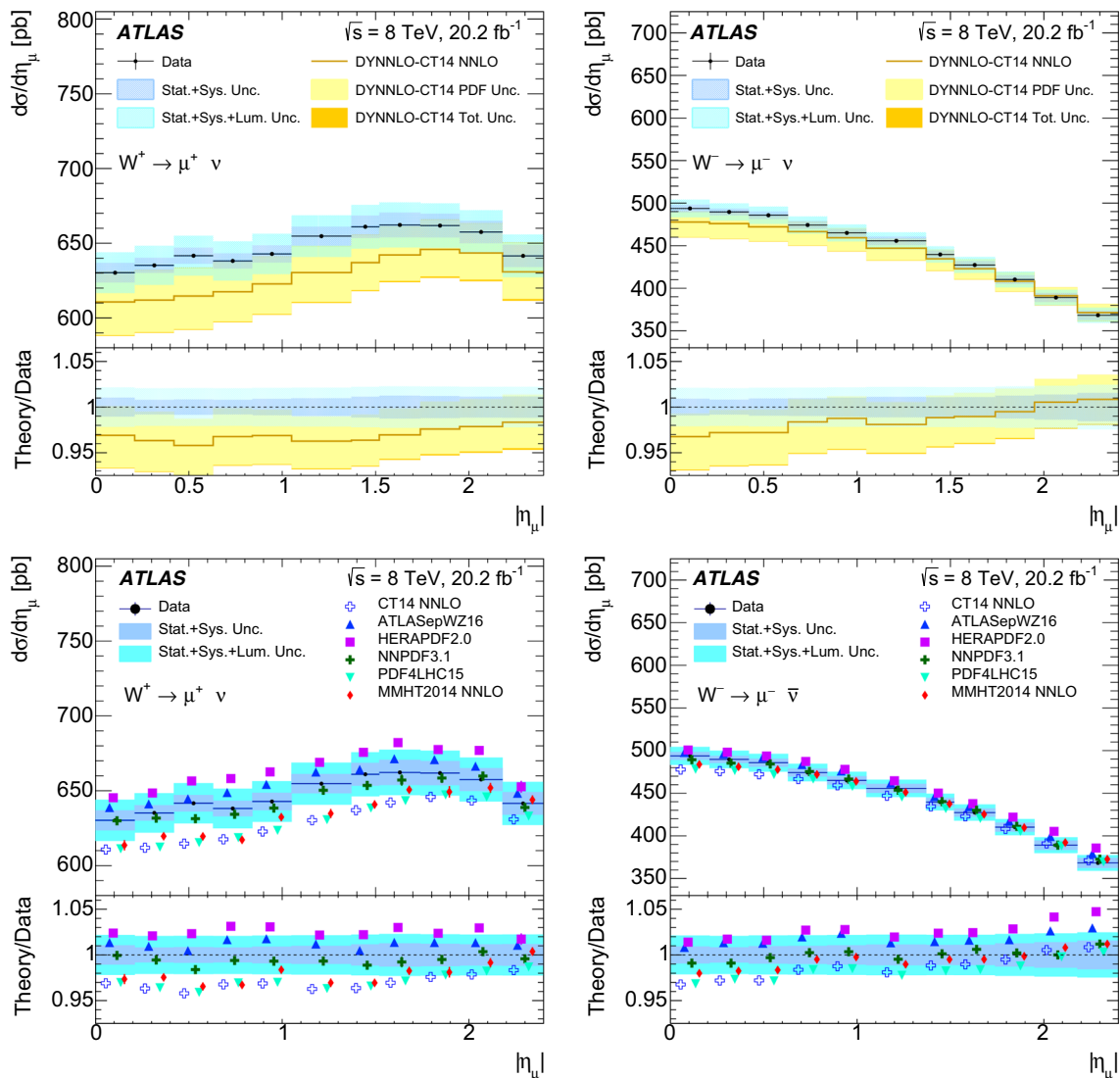
Uncertainties in the DYNNLO prediction due the choice of scales are evaluated by varying the factorisation and renormalisation scales independently by factors of 0.5 and 2 from their nominal values. The uncertainty on the CT14 NNLO prediction is evaluated using the corresponding PDF error sets.

## 6 Results

The measured integrated fiducial cross-sections multiplied by the branching fraction for the decay into a muon and a neutrino are listed in Table 4, along with the associated uncertainties which are dominated by the 1.9% uncertainty in the luminosity. Also provided is the sum of the  $W^+ \rightarrow \mu^+ \nu$  and  $W^- \rightarrow \mu^- \bar{\nu}$  integrated cross-sections and their ratio, the total uncertainties on which are 2.1% and 0.3% respectively. The data are compared with the NNLO predictions from DYNNLO, the total uncertainties on which are dom-

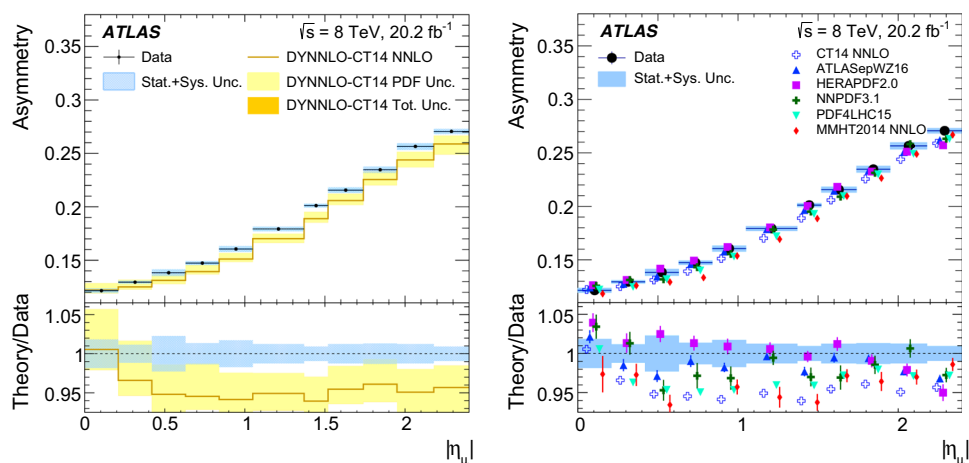
**Table 4** The measured fiducial production cross-sections times branching ratio for  $W^+ \rightarrow \mu^+ \nu$  and  $W^- \rightarrow \mu^- \bar{\nu}$ , their sum, and their ratio for both data and the predictions from DYNNLO (CT14 NNLO PDF set)

Data	
$\sigma(W^+ \rightarrow \mu^+ \nu)$ [pb]	$3110 \pm 0.5$ (stat.) $\pm 28$ (syst.) $\pm 59$ (lumi.)
$\sigma(W^- \rightarrow \mu^- \bar{\nu})$ [pb]	$2137 \pm 0.4$ (stat.) $\pm 21$ (syst.) $\pm 41$ (lumi.)
Sum [pb]	$5247 \pm 0.6$ (stat.) $\pm 49$ (syst.) $\pm 100$ (lumi.)
Ratio	$1.4558 \pm 0.0004$ (stat.) $\pm 0.0040$ (syst.)
DYNNLO (CT14 NNLO PDF set)	
$\sigma(W^+ \rightarrow \mu^+ \nu)$ [pb]	$3015 \pm 92$ (PDF) $\pm 15$ (scale)
$\sigma(W^- \rightarrow \mu^- \bar{\nu})$ [pb]	$2105 \pm 53$ (PDF) $\pm 10$ (scale)
Sum [pb]	$5120 \pm 140$ (PDF) $\pm 23$ (scale)
Ratio	$1.4320 \pm 0.0100$ (PDF) $\pm 0.0007$ (scale)



**Fig. 4** The  $W^+$  (left) and  $W^-$  (right) fiducial cross-sections, differential in muon pseudorapidity multiplied by the branching fraction for the decay into a muon and a neutrino are shown as a function of the absolute muon pseudorapidity. The data are presented with systematic and total uncertainties (the data statistical uncertainties are smaller than the size of the markers) and are compared with the predictions from

DYNNLO. In the top two plots, the CT14 NNLO PDF set is used, and DYNNLO is shown with its associated total theoretical uncertainty. In the bottom two plots, the data are compared with the central values of six different PDF sets described in the text. The statistical uncertainties of the DYNNLO predictions are indicated by error bars. The ratios of the data to the corresponding prediction are shown in the lower panels



**Fig. 5** The  $W$  boson charge asymmetry as a function of absolute muon pseudorapidity. The data are presented with systematic and total uncertainties (the data statistical uncertainties are smaller than the size of the markers). In the left plot, the data are compared with the prediction from DYNNLO in which the CT14 NNLO PDF set is used. The DYNNLO prediction is also shown with its associated total theoretical

uncertainty, along with the component from the PDF set. In the right plot, the data are compared with the central prediction from DYNNLO produced using a selection of PDFs. The statistical uncertainties of the DYNNLO predictions are indicated by error bars. The ratios of the data to the corresponding prediction are shown in the lower panels

inated by the component from the PDF uncertainty. Data and theory agree well and within the uncertainties, although the ratio measurements differ by approximately two standard deviations. The results presented in Table 4 are consistent, within about one standard deviation, with those measured using  $W$  boson decays in the electron channel in data at a centre-of-mass energy of 8 TeV [63].

The  $W^+$  and  $W^-$  fiducial cross-sections, differential in muon pseudorapidity, multiplied by the branching fraction for the decay into a muon and a neutrino, are shown as a function of absolute muon pseudorapidity in Fig. 4. These are presented with systematic and total uncertainties. The data statistical uncertainties are smaller than the size of the markers. The cross-section values are detailed in Table 3. The measured cross-sections are compared with theoretical predictions obtained using DYNNLO.

In the top plots of Fig. 4, DYNNLO is shown with its associated total theoretical uncertainty, and from the PDF uncertainty (evaluated with the CT14 NNLO error sets). The component from the PDF uncertainty dominates the total and is shown separately. The data precision is similar to the intrinsic theoretical uncertainty from scale variations but is much higher than the uncertainty from the PDF. Therefore the data are useful for constraining and evaluating the performance of different PDF sets. In the bottom plots the data are compared with the central values of each PDF set described above. The statistical uncertainties of the DYNNLO predictions are indicated by error bars.

The measured  $W$  boson charge asymmetry as a function of absolute muon pseudorapidity is presented in Fig. 5. The values are detailed in Table 3. Again the data are shown with

its total systematic uncertainty. In Fig. 5 (left) the data are compared with the prediction from DYNNLO in which the CT14 NNLO PDF set is used. The DYNNLO prediction is also shown with its associated total theoretical uncertainty, along with the component from the PDF set, which dominates. In Fig. 5 (right) the data are compared with the central prediction from the six PDF sets considered. The statistical uncertainties of the DYNNLO predictions are indicated by error bars. The ratios of the data to the corresponding prediction are shown in the lower panels. The comparison with ATLASepWZ2016 and NNPDF3.1 is of particular interest as both include information from the ATLAS 7 TeV measurement [2], which is expected to be largely uncorrelated with the current data being presented. It is observed that its central value is generally closer to the data than the alternatives, other than HERAPDF2.0 which performs about as well.

## 7 Conclusion

Fiducial cross-sections for  $W^+ \rightarrow \mu^+ \nu$  and  $W^- \rightarrow \mu^- \bar{\nu}$  and the  $W$  boson charge asymmetry are measured differentially as a function of the absolute muon pseudorapidity using 20.2 fb $^{-1}$  of data from proton–proton collisions at a centre-of-mass energy of 8 TeV with the ATLAS experiment at the LHC. The muon and neutrino transverse momenta are required to be greater than 25 GeV and the  $W$  boson transverse mass to be greater than 40 GeV. A precision of 0.8–1.5% is achieved for the cross-section values, depending on the pseudorapidity, whilst an uncertainty between 0.002 and 0.003 (in absolute units) is obtained for the asymmetry. The

integrated fiducial  $W^\pm$  production cross-sections are also determined. The measurements are compared to predictions at NNLO accuracy in QCD computed with the DYNLO program. The precision of the measurement is better than both the uncertainties on the PDF sets as well as the spread between different sets, showing the sensitivity of the measurement to discriminate between them and serve as input to improve the knowledge on the proton structure.

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**Data Availability Statement** This manuscript has no associated data or the data will not be deposited [Authors' comment: All ATLAS scientific output is published in journals, and preliminary results are made available in Conference Notes. All are openly available, without restriction on use by external parties beyond copyright law and the standard conditions agreed by CERN. Data associated with journal publications are also made available: tables and data from plots (e.g. cross section values, likelihood profiles, selection efficiencies, cross section limits,...) are stored in appropriate repositories such as HEPDATA (<http://hepdata.cedar.ac.uk/>). ATLAS also strives to make additional material related to the paper available that allows a reinterpretation of the data in the context of new theoretical models. For example, an extended encapsulation of the analysis is often provided for measurements in the framework of RIVET (<http://rivet.hepforge.org/>).] This information is taken from the ATLAS Data Access Policy, which is a public document that can be downloaded from <http://opendata.cern.ch/record/413>.]

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## ATLAS Collaboration

G. Aad<sup>101</sup>, B. Abbott<sup>128</sup>, D. C. Abbott<sup>102</sup>, O. Abdinov<sup>13,\*</sup>, A. Abed Abud<sup>70a,70b</sup>, K. Abeling<sup>53</sup>, D. K. Abhayasinghe<sup>93</sup>, S. H. Abidi<sup>167</sup>, O. S. AbouZeid<sup>40</sup>, N. L. Abraham<sup>156</sup>, H. Abramowicz<sup>161</sup>, H. Abreu<sup>160</sup>, Y. Abulaiti<sup>6</sup>, B. S. Acharya<sup>66a,66b,n</sup>, B. Achkar<sup>53</sup>, S. Adachi<sup>163</sup>, L. Adam<sup>99</sup>, C. Adam Bourdarios<sup>132</sup>, L. Adamczyk<sup>83a</sup>, L. Adamek<sup>167</sup>, J. Adelman<sup>121</sup>, M. Adersberger<sup>114</sup>, A. Adiguzel<sup>12c,ah</sup>, S. Adorni<sup>54</sup>, T. Adye<sup>144</sup>, A. A. Affolder<sup>146</sup>, Y. Afik<sup>160</sup>, C. Agapopoulou<sup>132</sup>, M. N. Agaras<sup>38</sup>, A. Aggarwal<sup>119</sup>, C. Agheorghiesei<sup>27c</sup>, J. A. Aguilar-Saavedra<sup>140f,140a,ag</sup>, F. Ahmadov<sup>79</sup>, X. Ai<sup>15a</sup>, G. Aielli<sup>73a,73b</sup>, S. Akatsuka<sup>85</sup>, T. P. A. Åkesson<sup>96</sup>, E. Akilli<sup>54</sup>, A. V. Akimov<sup>110</sup>, K. Al Khoury<sup>132</sup>, G. L. Alberghi<sup>23a,23b</sup>, J. Albert<sup>176</sup>, M. J. Alconada Verzini<sup>88</sup>, S. Alderweireldt<sup>119</sup>, M. Aleksa<sup>36</sup>, I. N. Aleksandrov<sup>79</sup>, C. Alexa<sup>27b</sup>, D. Alexandre<sup>19</sup>, T. Alexopoulos<sup>10</sup>, A. Alfonsi<sup>120</sup>, M. Alhroob<sup>128</sup>, B. Ali<sup>142</sup>, G. Alimonti<sup>68a</sup>, J. Alison<sup>37</sup>, S. P. Alkire<sup>148</sup>, C. Allaire<sup>132</sup>, B. M. M. Allbrooke<sup>156</sup>, B. W. Allen<sup>131</sup>, P. P. Allport<sup>21</sup>, A. Aloisio<sup>69a,69b</sup>, A. Alonso<sup>40</sup>, F. Alonso<sup>88</sup>, C. Alpigiani<sup>148</sup>, A. A. Alshehri<sup>57</sup>, M. Alvarez Estevez<sup>98</sup>, B. Alvarez Gonzalez<sup>36</sup>, D. Álvarez Piqueras<sup>174</sup>, M. G. Alvigi<sup>69a,69b</sup>, Y. Amaral Coutinho<sup>80b</sup>, A. Ambler<sup>103</sup>, L. Ambroz<sup>135</sup>, C. Amelung<sup>26</sup>, D. Amidei<sup>105</sup>, S. P. Amor Dos Santos<sup>140a</sup>, S. Amoroso<sup>46</sup>, C. S. Amrouche<sup>54</sup>, F. An<sup>78</sup>, C. Anastopoulos<sup>149</sup>, N. Andari<sup>145</sup>, T. Andeen<sup>11</sup>, C. F. Anders<sup>61b</sup>, J. K. Anders<sup>20</sup>, A. Andreazza<sup>68a,68b</sup>, V. Andrei<sup>61a</sup>, C. R. Anelli<sup>176</sup>, S. Angelidakis<sup>38</sup>, A. Angerami<sup>39</sup>, A. V. Anisenkov<sup>122a,122b</sup>, A. Annovi<sup>71a</sup>, C. Antel<sup>61a</sup>, M. T. Anthony<sup>149</sup>, M. Antonelli<sup>51</sup>, D. J. A. Antrim<sup>171</sup>, F. Anulli<sup>72a</sup>, M. Aoki<sup>81</sup>, J. A. Aparisi Pozo<sup>174</sup>, L. Aperio Bella<sup>36</sup>, G. Arabidze<sup>106</sup>, J. P. Araque<sup>140a</sup>, V. Araujo Ferraz<sup>80b</sup>, R. Araujo Pereira<sup>80b</sup>, C. Arcangeletti<sup>51</sup>, A. T. H. Arce<sup>49</sup>, F. A. Arduh<sup>88</sup>, J-F. Arguin<sup>109</sup>, S. Argyropoulos<sup>77</sup>, J.-H. Arling<sup>46</sup>, A. J. Armbruster<sup>36</sup>, L. J. Armitage<sup>92</sup>, A. Armstrong<sup>171</sup>, O. Arnaez<sup>167</sup>, H. Arnold<sup>120</sup>, A. Artamonov<sup>111,\*</sup>, G. Artoni<sup>135</sup>, S. Artz<sup>99</sup>, S. Asai<sup>163</sup>, N. Asbah<sup>59</sup>, E. M. Asimakopoulou<sup>172</sup>, L. Asquith<sup>156</sup>, K. Assamagan<sup>29</sup>, R. Astalos<sup>28a</sup>, R. J. Atkin<sup>33a</sup>, M. Atkinson<sup>173</sup>, N. B. Atlay<sup>151</sup>, H. Atmani<sup>132</sup>, K. Augsten<sup>142</sup>, G. Avolio<sup>36</sup>, R. Avramidou<sup>60a</sup>, M. K. Ayoub<sup>15a</sup>, A. M. Azoulay<sup>168b</sup>, G. Azuelos<sup>109,av</sup>, M. J. Baca<sup>21</sup>, H. Bachacou<sup>145</sup>, K. Bachas<sup>67a,67b</sup>, M. Backes<sup>135</sup>, F. Backman<sup>45a,45b</sup>, P. Bagnaia<sup>72a,72b</sup>, M. Bahmani<sup>84</sup>, H. Bahrasemani<sup>152</sup>, A. J. Bailey<sup>174</sup>, V. R. Bailey<sup>173</sup>, J. T. Baines<sup>144</sup>, M. Bajic<sup>40</sup>, C. Bakalis<sup>10</sup>, O. K. Baker<sup>183</sup>, P. J. Bakker<sup>120</sup>, D. Bakshi Gupta<sup>8</sup>, S. Balaji<sup>157</sup>, E. M. Baldin<sup>122a,122b</sup>, P. Balek<sup>180</sup>, F. Balli<sup>145</sup>, W. K. Balunas<sup>135</sup>, J. Balz<sup>99</sup>, E. Banas<sup>84</sup>, A. Bandyopadhyay<sup>24</sup>, Sw. Banerjee<sup>181,i</sup>, A. A. E. Bannoura<sup>182</sup>, L. Barak<sup>161</sup>, W. M. Barbe<sup>38</sup>, E. L. Barberio<sup>104</sup>, D. Barberis<sup>55a,55b</sup>, M. Barbero<sup>101</sup>, T. Barillari<sup>115</sup>, M.-S. Barisits<sup>36</sup>, J. Barkeloo<sup>131</sup>, T. Barklow<sup>153</sup>, R. Barnea<sup>160</sup>, S. L. Barnes<sup>60c</sup>, B. M. Barnett<sup>144</sup>, R. M. Barnett<sup>18</sup>, Z. Barnovska-Blenessy<sup>60a</sup>, A. Baroncelli<sup>60a</sup>, G. Barone<sup>29</sup>, A. J. Barr<sup>135</sup>, L. Barranco Navarro<sup>174</sup>, F. Barreiro<sup>98</sup>, J. Barreiro Guimarães da Costa<sup>15a</sup>, R. Bartoldus<sup>153</sup>, G. Bartolini<sup>101</sup>, A. E. Barton<sup>89</sup>, P. Bartos<sup>28a</sup>, A. Basalaev<sup>46</sup>, A. Bassalat<sup>132</sup>, R. L. Bates<sup>57</sup>, S. J. Batista<sup>167</sup>, S. Batlamous<sup>35e</sup>, J. R. Batley<sup>32</sup>, B. Batool<sup>151</sup>, M. Battaglia<sup>146</sup>, M. Bauce<sup>72a,72b</sup>, F. Bauer<sup>145</sup>, K. T. Bauer<sup>171</sup>, H. S. Bawa<sup>31,i</sup>, J. B. Beacham<sup>126</sup>, T. Beau<sup>136</sup>, P. H. Beauchemin<sup>170</sup>, F. Becherer<sup>52</sup>, P. Bechtel<sup>24</sup>, H. C. Beck<sup>53</sup>, H. P. Beck<sup>20,q</sup>, K. Becker<sup>52</sup>, M. Becker<sup>99</sup>, C. Becot<sup>46</sup>, A. Beddall<sup>12d</sup>, A. J. Beddall<sup>12a</sup>, V. A. Bednyakov<sup>79</sup>, M. Bedognetti<sup>120</sup>, C. P. Bee<sup>155</sup>, T. A. Beermann<sup>76</sup>, M. Begalli<sup>80b</sup>, M. Begel<sup>29</sup>, A. Behera<sup>155</sup>, J. K. Behr<sup>46</sup>, F. Beisiegel<sup>24</sup>, A. S. Bell<sup>94</sup>, G. Bella<sup>161</sup>, L. Bellagamba<sup>23b</sup>, A. Bellerive<sup>34</sup>, P. Bellos<sup>9</sup>, K. Beloborodov<sup>122a,122b</sup>, K. Belotskiy<sup>112</sup>, N. L. Belyaev<sup>112</sup>, D. Benchechroun<sup>35a</sup>, N. Benekos<sup>10</sup>, Y. Benhammou<sup>161</sup>, D. P. Benjamin<sup>6</sup>, M. Benoit<sup>54</sup>, J. R. Bensinger<sup>26</sup>, S. Bentvelsen<sup>120</sup>, L. Beresford<sup>135</sup>, M. Beretta<sup>51</sup>, D. Berge<sup>46</sup>, E. Bergeas Kuutmann<sup>172</sup>, N. Berger<sup>5</sup>, B. Bergmann<sup>142</sup>, L. J. Bergsten<sup>26</sup>, J. Beringer<sup>18</sup>, S. Berlendis<sup>7</sup>, N. R. Bernard<sup>102</sup>, G. Bernardi<sup>136</sup>, C. Bernius<sup>153</sup>, F. U. Bernlochner<sup>24</sup>, T. Berry<sup>93</sup>, P. Berta<sup>99</sup>, C. Bertella<sup>15a</sup>, I. A. Bertram<sup>89</sup>, G. J. Besjes<sup>40</sup>, O. Bessidskaia Bylund<sup>182</sup>, N. Besson<sup>145</sup>, A. Bethani<sup>100</sup>, S. Bethke<sup>115</sup>, A. Betti<sup>24</sup>, A. J. Bevan<sup>92</sup>, J. Beyer<sup>115</sup>, R. Bi<sup>139</sup>, R. M. Bianchi<sup>139</sup>, O. Biebel<sup>114</sup>, D. Biedermann<sup>19</sup>, R. Bielski<sup>36</sup>, K. Bierwagen<sup>99</sup>, N. V. Biesuz<sup>71a,71b</sup>, M. Biglietti<sup>74a</sup>, T. R. V. Billoud<sup>109</sup>, M. Bindi<sup>53</sup>, A. Bingul<sup>12d</sup>, C. Bini<sup>72a,72b</sup>, S. Biondi<sup>23a,23b</sup>, M. Birman<sup>180</sup>, T. Bisanz<sup>53</sup>, J. P. Biswal<sup>161</sup>, A. Bitadze<sup>100</sup>, C. Bittrich<sup>48</sup>, K. Björke<sup>134</sup>, K. M. Black<sup>25</sup>, T. Blazek<sup>28a</sup>, I. Bloch<sup>46</sup>, C. Blocker<sup>26</sup>, A. Blue<sup>57</sup>, U. Blumenschein<sup>92</sup>, G. J. Bobbink<sup>120</sup>, V. S. Bobrovnikov<sup>122a,122b</sup>, S. S. Bocchetta<sup>96</sup>, A. Bocci<sup>49</sup>, D. Boerner<sup>46</sup>, D. Bogavac<sup>14</sup>, A. G. Bogdanchikov<sup>122a,122b</sup>, C. Boehm<sup>45a</sup>, V. Boisvert<sup>93</sup>, P. Boka<sup>53,172</sup>, T. Bold<sup>83a</sup>, A. S. Boldyrev<sup>113</sup>, A. E. Bolz<sup>61b</sup>, M. Bomben<sup>136</sup>, M. Bona<sup>92</sup>, J. S. Bonilla<sup>131</sup>, M. Boonekamp<sup>145</sup>, H. M. Borecka-Bielska<sup>90</sup>, A. Borisov<sup>123</sup>, G. Borissov<sup>89</sup>, J. Bortfeldt<sup>36</sup>, D. Bortoletto<sup>135</sup>, V. Bortolotto<sup>73a,73b</sup>, D. Boscherini<sup>23b</sup>, M. Bosman<sup>14</sup>, J. D. Bossio Sola<sup>103</sup>, K. Bouaouda<sup>35a</sup>, J. Boudreau<sup>139</sup>, E. V. Bouhova-Thacker<sup>89</sup>, D. Boumediene<sup>38</sup>, S. K. Boutle<sup>57</sup>, A. Boveia<sup>126</sup>, J. Boyd<sup>36</sup>, D. Boye<sup>33b,ap</sup>, I. R. Boyko<sup>79</sup>, A. J. Bozson<sup>93</sup>, J. Bracinik<sup>21</sup>, N. Brahimi<sup>101</sup>, G. Brandt<sup>182</sup>, O. Brandt<sup>61a</sup>, F. Braren<sup>46</sup>, U. Bratzler<sup>164</sup>, B. Brau<sup>102</sup>, J. E. Brau<sup>131</sup>, W. D. Breaden Madden<sup>57</sup>, K. Brendlinger<sup>46</sup>, L. Brenner<sup>46</sup>, R. Brenner<sup>172</sup>, S. Bressler<sup>180</sup>, B. Brickwedde<sup>99</sup>, D. L. Briglin<sup>21</sup>, D. Britton<sup>57</sup>, D. Britzger<sup>115</sup>, I. Brock<sup>24</sup>, R. Brock<sup>106</sup>, G. Brooijmans<sup>39</sup>, W. K. Brooks<sup>147b</sup>, E. Brost<sup>121</sup>, J. H. Broughton<sup>21</sup>, P. A. Bruckman de Renstrom<sup>84</sup>, D. Bruncko<sup>28b</sup>, A. Bruni<sup>23b</sup>, G. Bruni<sup>23b</sup>, L. S. Bruni<sup>120</sup>, S. Bruno<sup>73a,73b</sup>, B. H. Brunt<sup>32</sup>, M. Bruschi<sup>23b</sup>, N. Bruscino<sup>139</sup>, P. Bryant<sup>37</sup>, L. Bryngemark<sup>96</sup>, T. Buanes<sup>17</sup>, Q. Buat<sup>36</sup>, P. Buchholz<sup>151</sup>, A. G. Buckley<sup>57</sup>, I. A. Budagov<sup>79</sup>, M. K. Bugge<sup>134</sup>, F. Bühner<sup>52</sup>, O. Bulekov<sup>112</sup>, T. J. Burch<sup>121</sup>, S. Burdin<sup>90</sup>, C. D. Burgard<sup>120</sup>, A. M. Burger<sup>129</sup>, B. Burghgrave<sup>8</sup>, K. Burkhardt<sup>84</sup>

J. T. P. Burr<sup>46</sup>, V. Büscher<sup>99</sup>, E. Buschmann<sup>53</sup>, P. J. Bussey<sup>57</sup>, J. M. Butler<sup>25</sup>, C. M. Buttar<sup>57</sup>, J. M. Butterworth<sup>94</sup>, P. Butti<sup>36</sup>, W. Buttinger<sup>36</sup>, A. Buzatu<sup>158</sup>, A. R. Buzykaev<sup>122a,122b</sup>, G. Cabras<sup>23a,23b</sup>, S. Cabrera Urbán<sup>174</sup>, D. Caforio<sup>56</sup>, H. Cai<sup>173</sup>, V. M. M. Cairo<sup>153</sup>, O. Cakir<sup>4a</sup>, N. Calace<sup>36</sup>, P. Calafiura<sup>18</sup>, A. Calandri<sup>101</sup>, G. Calderini<sup>136</sup>, P. Calfayan<sup>65</sup>, G. Callea<sup>57</sup>, L. P. Caloba<sup>80b</sup>, S. Calvente Lopez<sup>98</sup>, D. Calvet<sup>38</sup>, S. Calvet<sup>38</sup>, T. P. Calvet<sup>155</sup>, M. Calvetti<sup>71a,71b</sup>, R. Camacho Toro<sup>136</sup>, S. Camarda<sup>36</sup>, D. Camarero Munoz<sup>98</sup>, P. Camarri<sup>73a,73b</sup>, D. Cameron<sup>134</sup>, R. Caminal Armadans<sup>102</sup>, C. Camincher<sup>36</sup>, S. Campana<sup>36</sup>, M. Campanelli<sup>94</sup>, A. Camplani<sup>40</sup>, A. Campoverde<sup>151</sup>, V. Canale<sup>69a,69b</sup>, A. Canesse<sup>103</sup>, M. Cano Bret<sup>60c</sup>, J. Cantero<sup>129</sup>, T. Cao<sup>161</sup>, Y. Cao<sup>173</sup>, M. D. M. Capeans Garrido<sup>36</sup>, M. Capua<sup>41a,41b</sup>, R. Cardarelli<sup>73a</sup>, F. C. Cardillo<sup>149</sup>, I. Carli<sup>143</sup>, T. Carli<sup>36</sup>, G. Carlino<sup>69a</sup>, B. T. Carlson<sup>139</sup>, L. Carminati<sup>68a,68b</sup>, R. M. D. Carney<sup>45a,45b</sup>, S. Caron<sup>119</sup>, E. Carquin<sup>147b</sup>, S. Carrá<sup>68a,68b</sup>, J. W. S. Carter<sup>167</sup>, M. P. Casado<sup>14e</sup>, A. F. Casha<sup>167</sup>, D. W. Casper<sup>171</sup>, R. Castellijn<sup>120</sup>, F. L. Castillo<sup>174</sup>, V. Castillo Gimenez<sup>174</sup>, N. F. Castro<sup>140a,140e</sup>, A. Catinaccio<sup>36</sup>, J. R. Catmore<sup>134</sup>, A. Cattai<sup>36</sup>, J. Caudron<sup>24</sup>, V. Cavaliere<sup>29</sup>, E. Cavallaro<sup>14</sup>, D. Cavalli<sup>68a</sup>, M. Cavalli-Sforza<sup>14</sup>, V. Cavasinni<sup>71a,71b</sup>, E. Celebi<sup>12b</sup>, F. Ceradini<sup>74a,74b</sup>, L. Cerda Alberich<sup>174</sup>, A. S. Cerqueira<sup>80a</sup>, A. Cerri<sup>156</sup>, L. Cerrito<sup>73a,73b</sup>, F. Cerutti<sup>18</sup>, A. Cervelli<sup>23a,23b</sup>, S. A. Cetin<sup>12b</sup>, D. Chakraborty<sup>121</sup>, S. K. Chan<sup>59</sup>, W. S. Chan<sup>120</sup>, W. Y. Chan<sup>90</sup>, J. D. Chapman<sup>32</sup>, B. Chargeishvili<sup>159b</sup>, D. G. Charlton<sup>21</sup>, T. P. Charman<sup>92</sup>, C. C. Chau<sup>34</sup>, S. Che<sup>126</sup>, A. Chegwiddden<sup>106</sup>, S. Chekanov<sup>6</sup>, S. V. Chekulaev<sup>168a</sup>, G. A. Chelkov<sup>79,au</sup>, M. A. Chelstowska<sup>36</sup>, B. Chen<sup>78</sup>, C. Chen<sup>60a</sup>, C. H. Chen<sup>78</sup>, H. Chen<sup>29</sup>, J. Chen<sup>60a</sup>, J. Chen<sup>39</sup>, S. Chen<sup>137</sup>, S. J. Chen<sup>15c</sup>, X. Chen<sup>15b,at</sup>, Y. Chen<sup>82</sup>, Y.-H. Chen<sup>46</sup>, H. C. Cheng<sup>63a</sup>, H. J. Cheng<sup>15a,15d</sup>, A. Cheplakov<sup>79</sup>, E. Cheremushkina<sup>123</sup>, R. Cherkaoui El Moursli<sup>35e</sup>, E. Cheu<sup>7</sup>, K. Cheung<sup>64</sup>, T. J. A. Chevalérias<sup>145</sup>, L. Chevalier<sup>145</sup>, V. Chiarella<sup>51</sup>, G. Chiarelli<sup>71a</sup>, G. Chiodini<sup>67a</sup>, A. S. Chisholm<sup>21,36</sup>, A. Chitan<sup>27b</sup>, I. Chiu<sup>163</sup>, Y. H. Chiu<sup>176</sup>, M. V. Chizhov<sup>79</sup>, K. Choi<sup>65</sup>, A. R. Chomont<sup>132</sup>, S. Chouridou<sup>162</sup>, Y. S. Chow<sup>120</sup>, M. C. Chu<sup>63a</sup>, J. Chudoba<sup>141</sup>, A. J. Chuinard<sup>103</sup>, J. J. Chwastowski<sup>84</sup>, L. Chytka<sup>130</sup>, K. M. Ciesla<sup>84</sup>, D. Cinca<sup>47</sup>, V. Cindro<sup>91</sup>, I. A. Cioară<sup>27b</sup>, A. Ciochio<sup>18</sup>, F. Ciotto<sup>69a,69b</sup>, Z. H. Citron<sup>180</sup>, M. Citterio<sup>68a</sup>, D. A. Ciubotaru<sup>27b</sup>, B. M. Ciungu<sup>167</sup>, A. Clark<sup>54</sup>, M. R. Clark<sup>39</sup>, P. J. Clark<sup>50</sup>, C. Clement<sup>45a,45b</sup>, Y. Coadou<sup>101</sup>, M. Cobal<sup>66a,66c</sup>, A. Coccaro<sup>55b</sup>, J. Cochran<sup>78</sup>, H. Cohen<sup>161</sup>, A. E. C. Coimbra<sup>36</sup>, L. Colasurdo<sup>119</sup>, B. Cole<sup>39</sup>, A. P. Colijn<sup>120</sup>, J. Collot<sup>58</sup>, P. Conde Muño<sup>140a,f</sup>, E. Coniavitis<sup>52</sup>, S. H. Connell<sup>33b</sup>, I. A. Connelly<sup>57</sup>, S. Constantinescu<sup>27b</sup>, F. Conventi<sup>69a,aw</sup>, A. M. Cooper-Sarkar<sup>135</sup>, F. Cormier<sup>175</sup>, K. J. R. Cormier<sup>167</sup>, L. D. Corpe<sup>94</sup>, M. Corradi<sup>72a,72b</sup>, E. E. Corrigan<sup>96</sup>, F. Corriveau<sup>103,ac</sup>, A. Cortes-Gonzalez<sup>36</sup>, M. J. Costa<sup>174</sup>, F. Costanza<sup>5</sup>, D. Costanzo<sup>149</sup>, G. Cowan<sup>93</sup>, J. W. Cowley<sup>32</sup>, J. Crane<sup>100</sup>, K. Cranmer<sup>124</sup>, S. J. Crawley<sup>57</sup>, R. A. Creager<sup>137</sup>, S. Crépe-Renaudin<sup>58</sup>, F. Crescioli<sup>136</sup>, M. Cristinziani<sup>24</sup>, V. Croft<sup>120</sup>, G. Crosetti<sup>41a,41b</sup>, A. Cueto<sup>5</sup>, T. Cuhadar Donszelmann<sup>149</sup>, A. R. Cukierman<sup>153</sup>, S. Czekiarda<sup>84</sup>, P. Czodrowski<sup>36</sup>, M. J. Da Cunha Sargedas De Sousa<sup>60b</sup>, J. V. Da Fonseca Pinto<sup>80b</sup>, C. Da Via<sup>100</sup>, W. Dabrowski<sup>83a</sup>, T. Dado<sup>28a</sup>, S. Dahbi<sup>35e</sup>, T. Dai<sup>105</sup>, C. Dallapiccola<sup>102</sup>, M. Dam<sup>40</sup>, G. D'amen<sup>23a,23b</sup>, V. D'Amico<sup>74a,74b</sup>, J. Damp<sup>99</sup>, J. R. Dandoy<sup>137</sup>, M. F. Daneri<sup>30</sup>, N. P. Dang<sup>181</sup>, N. D. Dann<sup>100</sup>, M. Danninger<sup>175</sup>, V. Dao<sup>36</sup>, G. Darbo<sup>55b</sup>, O. Dartsis<sup>5</sup>, A. Dattagupta<sup>131</sup>, T. Daubney<sup>46</sup>, S. D'Auria<sup>68a,68b</sup>, W. Davey<sup>24</sup>, C. David<sup>46</sup>, T. Davidek<sup>143</sup>, D. R. Davis<sup>49</sup>, E. Dawe<sup>104</sup>, I. Dawson<sup>149</sup>, K. De<sup>8</sup>, R. De Asmundis<sup>69a</sup>, M. De Beurs<sup>120</sup>, S. De Castro<sup>23a,23b</sup>, S. De Cecco<sup>72a,72b</sup>, N. De Groot<sup>119</sup>, P. de Jong<sup>120</sup>, H. De la Torre<sup>106</sup>, A. De Maria<sup>15c</sup>, D. De Pedis<sup>72a</sup>, A. De Salvo<sup>72a</sup>, U. De Sanctis<sup>73a,73b</sup>, M. De Santis<sup>73a,73b</sup>, A. De Santo<sup>156</sup>, K. De Vasconcelos Corga<sup>101</sup>, J. B. De Vivie De Regie<sup>132</sup>, C. Debenedetti<sup>146</sup>, D. V. Dedovich<sup>79</sup>, A. M. Deiana<sup>42</sup>, M. Del Gaudio<sup>41a,41b</sup>, J. Del Peso<sup>98</sup>, Y. Delabat Diaz<sup>46</sup>, D. Delgove<sup>132</sup>, F. Deliot<sup>145</sup>, C. M. Delitzsch<sup>7</sup>, M. Della Pietra<sup>69a,69b</sup>, D. Della Volpe<sup>54</sup>, A. Dell'Acqua<sup>36</sup>, L. Dell'Asta<sup>73a,73b</sup>, M. Delmastro<sup>5</sup>, C. Delporte<sup>132</sup>, P. A. Delsart<sup>58</sup>, D. A. DeMarco<sup>167</sup>, S. Demers<sup>183</sup>, M. Demichev<sup>79</sup>, G. Demontigny<sup>109</sup>, S. P. Denisov<sup>123</sup>, D. Denysiuk<sup>120</sup>, L. D'Eramo<sup>136</sup>, D. Derendarz<sup>84</sup>, J. E. Derkaoui<sup>35d</sup>, F. Derue<sup>136</sup>, P. Dervan<sup>90</sup>, K. Desch<sup>24</sup>, C. Deterre<sup>46</sup>, K. Dette<sup>167</sup>, C. Deutsch<sup>24</sup>, M. R. Devesa<sup>30</sup>, P. O. Deviveiros<sup>36</sup>, A. Dewhurst<sup>144</sup>, S. Dhaliwal<sup>26</sup>, F. A. Di Bello<sup>54</sup>, A. Di Ciaccio<sup>73a,73b</sup>, L. Di Ciaccio<sup>5</sup>, W. K. Di Clemente<sup>137</sup>, C. Di Donato<sup>69a,69b</sup>, A. Di Girolamo<sup>36</sup>, G. Di Gregorio<sup>71a,71b</sup>, B. Di Micco<sup>74a,74b</sup>, R. Di Nardo<sup>102</sup>, K. F. Di Petrillo<sup>59</sup>, R. Di Sipio<sup>167</sup>, D. Di Valentino<sup>34</sup>, C. Diaconu<sup>101</sup>, F. A. Dias<sup>40</sup>, T. Dias Do Vale<sup>140a</sup>, M. A. Diaz<sup>147a</sup>, J. Dickinson<sup>18</sup>, E. B. Diehl<sup>105</sup>, J. Dietrich<sup>19</sup>, S. Díez Cornell<sup>46</sup>, A. Dimitrievska<sup>18</sup>, W. Ding<sup>15b</sup>, J. Dingfelder<sup>24</sup>, F. Dittus<sup>36</sup>, F. Djama<sup>101</sup>, T. Djobava<sup>159b</sup>, J. I. Djuvsland<sup>17</sup>, M. A. B. Do Vale<sup>80c</sup>, M. Dobre<sup>27b</sup>, D. Dodsworth<sup>26</sup>, C. Doglioni<sup>96</sup>, J. Dolejsi<sup>143</sup>, Z. Dolezal<sup>143</sup>, M. Donadelli<sup>80d</sup>, J. Donini<sup>38</sup>, A. D'onofrio<sup>92</sup>, M. D'Onofrio<sup>90</sup>, J. Dopke<sup>144</sup>, A. Doria<sup>69a</sup>, M. T. Dova<sup>88</sup>, A. T. Doyle<sup>57</sup>, E. Drechsler<sup>152</sup>, E. Dreyer<sup>152</sup>, T. Dreyer<sup>53</sup>, Y. Duan<sup>60b</sup>, F. Dubinin<sup>110</sup>, M. Dubovsky<sup>28a</sup>, A. Dubreuil<sup>54</sup>, E. Duchovni<sup>180</sup>, G. Duckeck<sup>114</sup>, A. Ducourthial<sup>136</sup>, O. A. Ducu<sup>109</sup>, D. Duda<sup>115</sup>, A. Dudarev<sup>36</sup>, A. C. Dudder<sup>99</sup>, E. M. Duffield<sup>18</sup>, L. Duflot<sup>132</sup>, M. Dührssen<sup>36</sup>, C. Dülsen<sup>182</sup>, M. Dumancic<sup>180</sup>, A. E. Dumitriu<sup>27b</sup>, A. K. Duncan<sup>57</sup>, M. Dunford<sup>61a</sup>, A. Duperrin<sup>101</sup>, H. Duran Yildiz<sup>4a</sup>, M. Düren<sup>56</sup>, A. Durglishvili<sup>159b</sup>, D. Duschinger<sup>48</sup>, B. Dutta<sup>46</sup>, D. Duvnjak<sup>1</sup>, G. I. Dyckes<sup>137</sup>, M. Dyndal<sup>36</sup>, S. Dysch<sup>100</sup>, B. S. Dziedzic<sup>84</sup>, K. M. Ecker<sup>115</sup>, R. C. Edgar<sup>105</sup>, T. Eifert<sup>36</sup>, G. Eigen<sup>17</sup>, K. Einsweiler<sup>18</sup>, T. Ekelof<sup>172</sup>, M. El Kacimi<sup>35c</sup>, R. El Kosseifi<sup>101</sup>, V. Ellajosyula<sup>172</sup>, M. Ellert<sup>172</sup>, F. Ellinghaus<sup>182</sup>, A. A. Elliot<sup>92</sup>, N. Ellis<sup>36</sup>, J. Elmsheuser<sup>29</sup>, M. Elsing<sup>36</sup>, D. Emeliyanov<sup>144</sup>, A. Emerman<sup>39</sup>, Y. Enari<sup>163</sup>, J. S. Ennis<sup>178</sup>, M. B. Epland<sup>49</sup>, J. Erdmann<sup>47</sup>, A. Ereditato<sup>20</sup>, M. Errenst<sup>36</sup>, M. Escalier<sup>132</sup>, C. Escobar<sup>174</sup>, O. Estrada Pastor<sup>174</sup>, E. Etzion<sup>161</sup>, H. Evans<sup>65</sup>, A. Ezhilov<sup>138</sup>, F. Fabbri<sup>57</sup>, L. Fabbri<sup>23a,23b</sup>, V. Fabiani<sup>119</sup>, G. Facini<sup>94</sup>

R. M. Faisca Rodrigues Pereira<sup>140a</sup>, R. M. Fakhrutdinov<sup>123</sup>, S. Falciano<sup>72a</sup>, P. J. Falke<sup>5</sup>, S. Falke<sup>5</sup>, J. Faltova<sup>143</sup>, Y. Fang<sup>15a</sup>, Y. Fang<sup>15a</sup>, G. Fanourakis<sup>44</sup>, M. Fanti<sup>68a,68b</sup>, A. Farbin<sup>8</sup>, A. Farilla<sup>74a</sup>, E. M. Farina<sup>70a,70b</sup>, T. Farooque<sup>106</sup>, S. Farrell<sup>18</sup>, S. M. Farrington<sup>178</sup>, P. Farthouat<sup>36</sup>, F. Fassi<sup>35e</sup>, P. Fassnacht<sup>36</sup>, D. Fassouliotis<sup>9</sup>, M. Faucci Giannelli<sup>50</sup>, W. J. Fawcett<sup>32</sup>, L. Fayard<sup>132</sup>, O. L. Fedin<sup>138,o</sup>, W. Fedorko<sup>175</sup>, M. Feickert<sup>42</sup>, S. Feigl<sup>134</sup>, L. Feligioni<sup>101</sup>, A. Fell<sup>149</sup>, C. Feng<sup>60b</sup>, E. J. Feng<sup>36</sup>, M. Feng<sup>49</sup>, M. J. Fenton<sup>57</sup>, A. B. Fenyuk<sup>123</sup>, J. Ferrando<sup>46</sup>, A. Ferrante<sup>173</sup>, A. Ferrari<sup>172</sup>, P. Ferrari<sup>120</sup>, R. Ferrari<sup>70a</sup>, D. E. Ferreira de Lima<sup>61b</sup>, A. Ferrer<sup>174</sup>, D. Ferrere<sup>54</sup>, C. Ferretti<sup>105</sup>, F. Fiedler<sup>99</sup>, A. Filipčić<sup>91</sup>, F. Filthaut<sup>119</sup>, K. D. Finelli<sup>25</sup>, M. C. N. Fiolhais<sup>140a</sup>, L. Fiorini<sup>174</sup>, F. Fischer<sup>114</sup>, W. C. Fisher<sup>106</sup>, I. Fleck<sup>151</sup>, P. Fleischmann<sup>105</sup>, R. R. M. Fletcher<sup>137</sup>, T. Flick<sup>182</sup>, B. M. Flierl<sup>114</sup>, L. F. Flores<sup>137</sup>, L. R. Flores Castillo<sup>63a</sup>, F. M. Follega<sup>75a,75b</sup>, N. Fomin<sup>17</sup>, G. T. Forcolin<sup>75a,75b</sup>, A. Formica<sup>145</sup>, F. A. Förster<sup>14</sup>, A. C. Forti<sup>100</sup>, A. G. Foster<sup>21</sup>, M. G. Foti<sup>135</sup>, D. Fournier<sup>132</sup>, H. Fox<sup>89</sup>, P. Francavilla<sup>71a,71b</sup>, S. Francescato<sup>72a,72b</sup>, M. Franchini<sup>23a,23b</sup>, S. Franchino<sup>61a</sup>, D. Francis<sup>36</sup>, L. Franconi<sup>20</sup>, M. Franklin<sup>59</sup>, A. N. Fray<sup>92</sup>, B. Freund<sup>109</sup>, W. S. Freund<sup>80b</sup>, E. M. Freundlich<sup>47</sup>, D. C. Frizzell<sup>128</sup>, D. Froidevaux<sup>36</sup>, J. A. Frost<sup>135</sup>, C. Fukunaga<sup>164</sup>, E. Fullana Torregrosa<sup>174</sup>, E. Fumagalli<sup>55a,55b</sup>, T. Fusayasu<sup>116</sup>, J. Fuster<sup>174</sup>, A. Gabrielli<sup>23a,23b</sup>, A. Gabrielli<sup>18</sup>, G. P. Gach<sup>83a</sup>, S. Gadatsch<sup>54</sup>, P. Gadow<sup>115</sup>, G. Gagliardi<sup>55a,55b</sup>, L. G. Gagnon<sup>109</sup>, C. Galea<sup>27b</sup>, B. Galhardo<sup>140a</sup>, G. E. Gallardo<sup>135</sup>, E. J. Gallas<sup>135</sup>, B. J. Gallop<sup>144</sup>, P. Gallus<sup>142</sup>, G. Galster<sup>40</sup>, R. Gamboa Goni<sup>92</sup>, K. K. Gan<sup>126</sup>, S. Ganguly<sup>180</sup>, J. Gao<sup>60a</sup>, Y. Gao<sup>90</sup>, Y. S. Gao<sup>31,l</sup>, C. García<sup>174</sup>, J. E. García Navarro<sup>174</sup>, J. A. García Pascual<sup>15a</sup>, C. Garcia-Argos<sup>52</sup>, M. Garcia-Sciveres<sup>18</sup>, R. W. Gardner<sup>37</sup>, N. Garelli<sup>153</sup>, S. Gargiulo<sup>52</sup>, V. Garonne<sup>134</sup>, A. Gaudiello<sup>55a,55b</sup>, G. Gaudio<sup>70a</sup>, I. L. Gavrilenko<sup>110</sup>, A. Gavrilyuk<sup>111</sup>, C. Gay<sup>175</sup>, G. Gaycken<sup>24</sup>, E. N. Gazizade<sup>10</sup>, A. A. Geanta<sup>27b</sup>, C. N. P. Gee<sup>144</sup>, J. Geisen<sup>53</sup>, M. Geisen<sup>99</sup>, M. P. Geisler<sup>61a</sup>, C. Gemme<sup>55b</sup>, M. H. Genest<sup>58</sup>, C. Geng<sup>105</sup>, S. Gentile<sup>72a,72b</sup>, S. George<sup>93</sup>, T. Gerasim<sup>44</sup>, D. Gerbaudo<sup>14</sup>, L. O. Gerlach<sup>53</sup>, P. Gessinger-Befurt<sup>99</sup>, G. Gessner<sup>47</sup>, S. Ghasemi<sup>151</sup>, M. Ghasemi Bostanabad<sup>176</sup>, M. Ghneimat<sup>24</sup>, A. Ghosh<sup>77</sup>, B. Giacobbe<sup>23b</sup>, S. Giagu<sup>72a,72b</sup>, N. Giangiacomi<sup>23a,23b</sup>, P. Giannetti<sup>71a</sup>, A. Giannini<sup>69a,69b</sup>, S. M. Gibson<sup>93</sup>, M. Gignac<sup>146</sup>, D. Gillberg<sup>34</sup>, G. Gilles<sup>182</sup>, D. M. Gingrich<sup>3,av</sup>, M. P. Giordani<sup>66a,66c</sup>, F. M. Giorgi<sup>23b</sup>, P. F. Giraud<sup>145</sup>, G. Giugliarelli<sup>66a,66c</sup>, D. Giugni<sup>68a</sup>, F. Giuli<sup>73a,73b</sup>, S. Gkaitatzis<sup>162</sup>, I. Gkialas<sup>9,h</sup>, E. L. Gkoukousis<sup>14</sup>, P. Gkoutoumis<sup>10</sup>, L. K. Gladilin<sup>113</sup>, C. Glasman<sup>98</sup>, J. Glatzer<sup>14</sup>, P. C. F. Glaysheer<sup>46</sup>, A. Glazov<sup>46</sup>, M. Goblirsch-Kolb<sup>26</sup>, S. Goldfarb<sup>104</sup>, T. Golling<sup>54</sup>, D. Golubkov<sup>123</sup>, A. Gomes<sup>140a,140b</sup>, R. Goncalves Gama<sup>53</sup>, R. Gonçalves<sup>140a,140b</sup>, G. Gonella<sup>52</sup>, L. Gonella<sup>21</sup>, A. Gongadze<sup>79</sup>, F. Gonnella<sup>21</sup>, J. L. Gonski<sup>59</sup>, S. González de la Hoz<sup>174</sup>, S. Gonzalez-Sevilla<sup>54</sup>, G. R. Gonzalvo Rodriguez<sup>174</sup>, L. Goossens<sup>36</sup>, P. A. Gorbounov<sup>111</sup>, H. A. Gordon<sup>29</sup>, B. Gorini<sup>36</sup>, E. Gorini<sup>67a,67b</sup>, A. Gorišek<sup>91</sup>, A. T. Goshaw<sup>49</sup>, C. Gössling<sup>47</sup>, M. I. Gostkin<sup>79</sup>, C. A. Gottardo<sup>24</sup>, M. Goughri<sup>35b</sup>, D. Goujdami<sup>35c</sup>, A. G. Goussiou<sup>148</sup>, N. Govender<sup>33b,a</sup>, C. Goy<sup>5</sup>, E. Gozani<sup>160</sup>, I. Grabowska-Bold<sup>83a</sup>, E. C. Graham<sup>90</sup>, J. Gramling<sup>171</sup>, E. Gramstad<sup>134</sup>, S. Grancagnolo<sup>19</sup>, M. Grandi<sup>156</sup>, V. Gratchev<sup>138</sup>, P. M. Gravila<sup>27f</sup>, F. G. Gravili<sup>67a,67b</sup>, C. Gray<sup>57</sup>, H. M. Gray<sup>18</sup>, C. Greife<sup>24</sup>, K. Gregersen<sup>96</sup>, I. M. Gregor<sup>46</sup>, P. Grenier<sup>153</sup>, K. Grevtsov<sup>46</sup>, N. A. Grieser<sup>128</sup>, J. Griffiths<sup>8</sup>, A. A. Grillo<sup>146</sup>, K. Grimm<sup>31,k</sup>, S. Grinstein<sup>14,w</sup>, J.-F. Grivaz<sup>132</sup>, S. Groh<sup>99</sup>, E. Gross<sup>180</sup>, J. Grosse-Knetter<sup>53</sup>, Z. J. Grout<sup>94</sup>, C. Grud<sup>105</sup>, A. Grummer<sup>118</sup>, L. Guan<sup>105</sup>, W. Guan<sup>181</sup>, J. Guenther<sup>36</sup>, A. Guerguichon<sup>132</sup>, F. Guescini<sup>168a</sup>, D. Guest<sup>171</sup>, R. Gugel<sup>52</sup>, B. Gui<sup>126</sup>, T. Guillemin<sup>5</sup>, S. Guindon<sup>36</sup>, U. Gul<sup>57</sup>, J. Guo<sup>60c</sup>, W. Guo<sup>105</sup>, Y. Guo<sup>60a,r</sup>, Z. Guo<sup>101</sup>, R. Gupta<sup>46</sup>, S. Gurbuz<sup>12c</sup>, G. Gustavino<sup>128</sup>, P. Gutierrez<sup>128</sup>, C. Gutsche<sup>94</sup>, C. Guyot<sup>145</sup>, M. P. Guzik<sup>83a</sup>, C. Gwenlan<sup>135</sup>, C. B. Gwilliam<sup>90</sup>, A. Haas<sup>124</sup>, C. Haber<sup>18</sup>, H. K. Hadavand<sup>8</sup>, N. Haddad<sup>35e</sup>, A. Hadeef<sup>60a</sup>, S. Hageböck<sup>36</sup>, M. Hagihara<sup>169</sup>, M. Haleem<sup>177</sup>, J. Haley<sup>129</sup>, G. Halladjian<sup>106</sup>, G. D. Hallowell<sup>101</sup>, K. Hamacher<sup>182</sup>, P. Hamal<sup>130</sup>, K. Hamano<sup>176</sup>, H. Hamdaoui<sup>35e</sup>, G. N. Hamity<sup>149</sup>, K. Han<sup>60a,aj</sup>, L. Han<sup>60a</sup>, S. Han<sup>15a,15d</sup>, K. Hanagaki<sup>81,u</sup>, M. Hance<sup>146</sup>, D. M. Handl<sup>114</sup>, B. Haney<sup>137</sup>, R. Hankache<sup>136</sup>, P. Hanke<sup>61a</sup>, E. Hansen<sup>96</sup>, J. B. Hansen<sup>40</sup>, J. D. Hansen<sup>40</sup>, M. C. Hansen<sup>24</sup>, P. H. Hansen<sup>40</sup>, E. C. Hanson<sup>100</sup>, K. Hara<sup>169</sup>, A. S. Hard<sup>181</sup>, T. Harenberg<sup>182</sup>, S. Harkusha<sup>107</sup>, P. F. Harrison<sup>178</sup>, N. M. Hartmann<sup>114</sup>, Y. Hasegawa<sup>150</sup>, A. Hasib<sup>50</sup>, S. Hassani<sup>145</sup>, S. Haug<sup>20</sup>, R. Hauser<sup>106</sup>, L. B. Havener<sup>39</sup>, M. Havranek<sup>142</sup>, C. M. Hawkes<sup>21</sup>, R. J. Hawkins<sup>36</sup>, D. Hayden<sup>106</sup>, C. Hayes<sup>155</sup>, R. L. Hayes<sup>175</sup>, C. P. Hays<sup>135</sup>, J. M. Hays<sup>92</sup>, H. S. Hayward<sup>90</sup>, S. J. Haywood<sup>144</sup>, F. He<sup>60a</sup>, M. P. Heath<sup>50</sup>, V. Hedberg<sup>96</sup>, L. Heelan<sup>8</sup>, S. Heer<sup>24</sup>, K. K. Heidegger<sup>52</sup>, J. Heilman<sup>34</sup>, S. Heim<sup>46</sup>, T. Heim<sup>18</sup>, B. Heinemann<sup>46,aq</sup>, J. J. Heinrich<sup>131</sup>, L. Heinrich<sup>36</sup>, C. Heinz<sup>56</sup>, J. Hejbal<sup>141</sup>, L. Helary<sup>61b</sup>, A. Held<sup>175</sup>, S. Hellesund<sup>134</sup>, C. M. Helling<sup>146</sup>, S. Hellman<sup>45a,45b</sup>, C. Helsens<sup>36</sup>, R. C. W. Henderson<sup>89</sup>, Y. Heng<sup>181</sup>, S. Henkelmann<sup>175</sup>, A. M. Henriques Correia<sup>36</sup>, G. H. Herbert<sup>19</sup>, H. Herde<sup>26</sup>, V. Herget<sup>177</sup>, Y. Hernández Jiménez<sup>33c</sup>, H. Herr<sup>99</sup>, M. G. Herrmann<sup>114</sup>, T. Herrmann<sup>48</sup>, G. Herten<sup>52</sup>, R. Hertenberger<sup>114</sup>, L. Hervas<sup>36</sup>, T. C. Herwig<sup>137</sup>, G. G. Hesketh<sup>94</sup>, N. P. Hessey<sup>168a</sup>, A. Higashida<sup>163</sup>, S. Higashino<sup>81</sup>, E. Higón-Rodríguez<sup>174</sup>, K. Hildebrand<sup>37</sup>, E. Hill<sup>176</sup>, J. C. Hill<sup>32</sup>, K. K. Hill<sup>29</sup>, K. H. Hiller<sup>46</sup>, S. J. Hillier<sup>21</sup>, M. Hils<sup>48</sup>, I. Hinchliffe<sup>18</sup>, F. Hinterkeuser<sup>24</sup>, M. Hirose<sup>133</sup>, S. Hirose<sup>52</sup>, D. Hirschbuehl<sup>182</sup>, B. Hiti<sup>91</sup>, O. Hladik<sup>141</sup>, D. R. Hlaluku<sup>33c</sup>, X. Hoad<sup>50</sup>, J. Hobbs<sup>155</sup>, N. Hod<sup>180</sup>, M. C. Hodgkinson<sup>149</sup>, A. Hoecker<sup>36</sup>, F. Hoenig<sup>114</sup>, D. Hohn<sup>52</sup>, D. Hohov<sup>132</sup>, T. R. Holmes<sup>37</sup>, M. Holzbock<sup>114</sup>, L. B. A. H. Hommels<sup>32</sup>, S. Honda<sup>169</sup>, T. Honda<sup>81</sup>, T. M. Hong<sup>139</sup>, A. Hönle<sup>115</sup>, B. H. Hooberman<sup>173</sup>, W. H. Hopkins<sup>6</sup>, Y. Horii<sup>117</sup>, P. Horn<sup>48</sup>, A. J. Horton<sup>152</sup>, L. A. Horyn<sup>37</sup>, J.-Y. Hostachy<sup>58</sup>, A. Hostiuc<sup>148</sup>, S. Hou<sup>158</sup>, A. Hoummada<sup>35a</sup>, J. Howarth<sup>100</sup>, J. Hoya<sup>88</sup>, M. Hrabovsky<sup>130</sup>, J. Hrdinka<sup>76</sup>,

I. Hristova<sup>19</sup>, J. Hrivnac<sup>132</sup>, A. Hrynevich<sup>108</sup>, T. Hryn'ova<sup>5</sup>, P. J. Hsu<sup>64</sup>, S.-C. Hsu<sup>148</sup>, Q. Hu<sup>29</sup>, S. Hu<sup>60c</sup>, Y. Huang<sup>15a</sup>, Z. Hubacek<sup>142</sup>, F. Hubaut<sup>101</sup>, M. Huebner<sup>24</sup>, F. Huegging<sup>24</sup>, T. B. Huffman<sup>135</sup>, M. Huhtinen<sup>36</sup>, R. F. H. Hunter<sup>34</sup>, P. Huo<sup>155</sup>, A. M. Hupe<sup>34</sup>, N. Huseynov<sup>79,ac</sup>, J. Huston<sup>106</sup>, J. Huth<sup>59</sup>, R. Hyneman<sup>105</sup>, S. Hyrych<sup>28a</sup>, G. Iacobucci<sup>54</sup>, G. Iakovidis<sup>29</sup>, I. Ibragimov<sup>151</sup>, L. Iconomidou-Fayard<sup>132</sup>, Z. Idrissi<sup>35e</sup>, P. I. Iengo<sup>36</sup>, R. Ignazzi<sup>40</sup>, O. Igonkina<sup>120,y</sup>, R. Iguchi<sup>163</sup>, T. Iizawa<sup>54</sup>, Y. Ikegami<sup>81</sup>, M. Ikeno<sup>81</sup>, D. Iliadis<sup>162</sup>, N. Ilic<sup>119</sup>, F. Iltzsche<sup>48</sup>, G. Introzzi<sup>70a,70b</sup>, M. Iodice<sup>74a</sup>, K. Iordanidou<sup>39</sup>, V. Ippolito<sup>72a,72b</sup>, M. F. Isacson<sup>172</sup>, N. Ishijima<sup>133</sup>, M. Ishino<sup>163</sup>, M. Ishitsuka<sup>165</sup>, W. Islam<sup>129</sup>, C. Issever<sup>135</sup>, S. Istin<sup>160</sup>, F. Ito<sup>169</sup>, J. M. Iturbe Ponce<sup>63a</sup>, R. Iuppa<sup>75a,75b</sup>, A. Ivina<sup>180</sup>, H. Iwasaki<sup>81</sup>, J. M. Izen<sup>43</sup>, V. Izzo<sup>69a</sup>, P. Jacka<sup>141</sup>, P. Jackson<sup>1</sup>, R. M. Jacobs<sup>24</sup>, V. Jain<sup>2</sup>, G. Jäkel<sup>182</sup>, K. B. Jakobi<sup>99</sup>, K. Jakobs<sup>52</sup>, S. Jakobsen<sup>76</sup>, T. Jakoubek<sup>141</sup>, J. Jamieson<sup>57</sup>, K. W. Janas<sup>83a</sup>, R. Jansky<sup>54</sup>, J. Janssen<sup>24</sup>, M. Janus<sup>53</sup>, P. A. Janus<sup>83a</sup>, G. Jarlskog<sup>96</sup>, N. Javadov<sup>79,ac</sup>, T. Javůrek<sup>36</sup>, M. Javurkova<sup>52</sup>, F. Jeanneau<sup>145</sup>, L. Jeanty<sup>131</sup>, J. Jejelava<sup>159a,af</sup>, A. Jelinskas<sup>178</sup>, P. Jenni<sup>52,b</sup>, J. Jeong<sup>46</sup>, N. Jeong<sup>46</sup>, S. Jézéquel<sup>5</sup>, H. Ji<sup>181</sup>, J. Jia<sup>155</sup>, H. Jiang<sup>78</sup>, Y. Jiang<sup>60a</sup>, Z. Jiang<sup>153,p</sup>, S. Jiggins<sup>52</sup>, F. A. Jimenez Morales<sup>38</sup>, J. Jimenez Pena<sup>174</sup>, S. Jin<sup>15c</sup>, A. Jinaru<sup>27b</sup>, O. Jinnouchi<sup>165</sup>, H. Jivan<sup>33c</sup>, P. Johansson<sup>149</sup>, K. A. Johns<sup>7</sup>, C. A. Johnson<sup>65</sup>, K. Jon-And<sup>45a,45b</sup>, R. W. L. Jones<sup>89</sup>, S. D. Jones<sup>156</sup>, S. Jones<sup>7</sup>, T. J. Jones<sup>90</sup>, J. Jongmanns<sup>61a</sup>, P. M. Jorge<sup>140a</sup>, J. Jovicevic<sup>36</sup>, X. Ju<sup>18</sup>, J. J. Junggeburth<sup>115</sup>, A. Juste Rozas<sup>14,w</sup>, A. Kaczmarzka<sup>84</sup>, M. Kado<sup>132</sup>, H. Kagan<sup>126</sup>, M. Kagan<sup>153</sup>, T. Kaji<sup>179</sup>, E. Kajomovitz<sup>160</sup>, C. W. Kalderon<sup>96</sup>, A. Kaluza<sup>99</sup>, A. Kamenshchikov<sup>123</sup>, L. Kanjir<sup>91</sup>, Y. Kano<sup>163</sup>, V. A. Kantserov<sup>112</sup>, J. Kanzaki<sup>81</sup>, L. S. Kaplan<sup>181</sup>, D. Kar<sup>33c</sup>, M. J. Kareem<sup>168b</sup>, E. Karentzos<sup>10</sup>, S. N. Karpov<sup>79</sup>, Z. M. Karpova<sup>79</sup>, V. Kartvelishvili<sup>89</sup>, A. N. Karyukhin<sup>123</sup>, L. Kashif<sup>181</sup>, R. D. Kass<sup>126</sup>, A. Kastanas<sup>45a,45b</sup>, Y. Kataoka<sup>163</sup>, C. Kato<sup>60c,60d</sup>, J. Katzy<sup>46</sup>, K. Kawade<sup>82</sup>, K. Kawagoe<sup>87</sup>, T. Kawaguchi<sup>117</sup>, T. Kawamoto<sup>163</sup>, G. Kawamura<sup>53</sup>, E. F. Kay<sup>176</sup>, V. F. Kazanin<sup>122a,122b</sup>, R. Keeler<sup>176</sup>, R. Kehoe<sup>42</sup>, J. S. Keller<sup>34</sup>, E. Kellermann<sup>163</sup>, D. Kelsey<sup>156</sup>, J. J. Kempster<sup>21</sup>, J. Kendrick<sup>21</sup>, O. Kepka<sup>141</sup>, S. Kersten<sup>182</sup>, B. P. Kerševan<sup>91</sup>, S. Ketabchi Haghighat<sup>167</sup>, M. Khader<sup>173</sup>, F. Khalil-Zada<sup>13</sup>, M. K. Khandoga<sup>145</sup>, A. Khanov<sup>129</sup>, A. G. Kharlamov<sup>122a,122b</sup>, T. Kharlamova<sup>122a,122b</sup>, E. E. Khoda<sup>175</sup>, A. Khodinov<sup>166</sup>, T. J. Khoo<sup>54</sup>, E. Khramov<sup>79</sup>, J. Khubua<sup>159b</sup>, S. Kido<sup>82</sup>, M. Kiehn<sup>54</sup>, C. R. Kilby<sup>93</sup>, Y. K. Kim<sup>37</sup>, N. Kimura<sup>66a,66c</sup>, O. M. Kind<sup>19</sup>, B. T. King<sup>90,\*</sup>, D. Kirchmeier<sup>48</sup>, J. Kirk<sup>144</sup>, A. E. Kiryunin<sup>115</sup>, T. Kishimoto<sup>163</sup>, D. P. Kisliuk<sup>167</sup>, V. Kitali<sup>46</sup>, O. Kivernyk<sup>5</sup>, E. Kladiva<sup>28b,\*</sup>, T. Klapdor-Kleingrothaus<sup>52</sup>, M. H. Klein<sup>105</sup>, M. Klein<sup>90</sup>, U. Klein<sup>90</sup>, K. Kleinknecht<sup>99</sup>, P. Klimek<sup>121</sup>, A. Klimentov<sup>29</sup>, T. Klingl<sup>24</sup>, T. Klioutchnikova<sup>36</sup>, F. F. Klitzner<sup>114</sup>, P. Kluit<sup>120</sup>, S. Kluth<sup>115</sup>, E. Kneringer<sup>76</sup>, E. B. F. G. Knoop<sup>101</sup>, A. Knuce<sup>52</sup>, D. Kobayashi<sup>87</sup>, T. Kobayashi<sup>163</sup>, M. Kobel<sup>48</sup>, M. Kocian<sup>153</sup>, P. Kodys<sup>143</sup>, P. T. Koenig<sup>24</sup>, T. Koffas<sup>34</sup>, N. M. Köhler<sup>115</sup>, T. Koi<sup>153</sup>, M. Kolb<sup>61b</sup>, I. Koletsou<sup>5</sup>, T. Komarek<sup>130</sup>, T. Kondo<sup>81</sup>, N. Kondrashova<sup>60c</sup>, K. Köneke<sup>52</sup>, A. C. König<sup>119</sup>, T. Kono<sup>125</sup>, R. Konoplich<sup>124,am</sup>, V. Konstantinides<sup>94</sup>, N. Konstantinidis<sup>94</sup>, B. Konya<sup>96</sup>, R. Kopeliansky<sup>65</sup>, S. Koperny<sup>83a</sup>, K. Korcyl<sup>84</sup>, K. Kordas<sup>162</sup>, G. Koren<sup>161</sup>, A. Korn<sup>94</sup>, I. Korolkov<sup>14</sup>, E. V. Korolkova<sup>149</sup>, N. Korotkova<sup>113</sup>, O. Kortner<sup>115</sup>, S. Kortner<sup>115</sup>, T. Kosek<sup>143</sup>, V. V. Kostyukhin<sup>24</sup>, A. Kotwal<sup>49</sup>, A. Koulouris<sup>10</sup>, A. Kourkoulis-Charalampidi<sup>70a,70b</sup>, C. Kourkoulis<sup>9</sup>, E. Kourlitis<sup>149</sup>, V. Kouskoura<sup>29</sup>, A. B. Kowalewska<sup>84</sup>, R. Kowalewski<sup>176</sup>, C. Kozakai<sup>163</sup>, W. Kozanecki<sup>145</sup>, A. S. Kozhin<sup>123</sup>, V. A. Kramarenko<sup>113</sup>, G. Kramberger<sup>91</sup>, D. Krasnopevtsev<sup>60a</sup>, M. W. Krasny<sup>136</sup>, A. Krasznahorkay<sup>36</sup>, D. Krauss<sup>115</sup>, J. A. Kremer<sup>83a</sup>, J. Kretzschmar<sup>90</sup>, P. Krieger<sup>167</sup>, F. Krieter<sup>114</sup>, A. Krishnan<sup>61b</sup>, K. Krizka<sup>18</sup>, K. Kroeninger<sup>47</sup>, H. Kroha<sup>115</sup>, J. Kroll<sup>141</sup>, J. Kroll<sup>137</sup>, J. Krstic<sup>16</sup>, U. Kruchonak<sup>79</sup>, H. Krüger<sup>24</sup>, N. Krumnack<sup>78</sup>, M. C. Kruse<sup>49</sup>, T. Kubota<sup>104</sup>, S. Kuday<sup>4b</sup>, J. T. Kuechler<sup>46</sup>, S. Kuehn<sup>36</sup>, A. Kugel<sup>161a</sup>, T. Kuhl<sup>46</sup>, V. Kukhtin<sup>79</sup>, R. Kukla<sup>101</sup>, Y. Kulchitsky<sup>107,ai</sup>, S. Kuleshov<sup>147b</sup>, Y. P. Kulinich<sup>173</sup>, M. Kuna<sup>58</sup>, T. Kunigo<sup>85</sup>, A. Kupco<sup>141</sup>, T. Kupfer<sup>47</sup>, O. Kuprash<sup>52</sup>, H. Kurashige<sup>82</sup>, L. L. Kurchaninov<sup>168a</sup>, Y. A. Kurochkin<sup>107</sup>, A. Kurova<sup>112</sup>, M. G. Kurth<sup>15a,15d</sup>, E. S. Kuwertz<sup>36</sup>, M. Kuze<sup>165</sup>, A. K. Kvam<sup>148</sup>, J. Kvita<sup>130</sup>, T. Kwan<sup>103</sup>, A. La Rosa<sup>115</sup>, L. La Rotonda<sup>41a,41b</sup>, F. La Ruffa<sup>41a,41b</sup>, C. Lacasta<sup>174</sup>, F. Lacava<sup>72a,72b</sup>, D. P. J. Lack<sup>100</sup>, H. Lacker<sup>19</sup>, D. Lacour<sup>136</sup>, E. Ladygin<sup>79</sup>, R. Lafaye<sup>5</sup>, B. Laforge<sup>136</sup>, T. Lagouri<sup>33c</sup>, S. Lai<sup>53</sup>, S. Lammers<sup>65</sup>, W. Lampl<sup>7</sup>, C. Lampoudis<sup>162</sup>, E. Lançon<sup>29</sup>, U. Landgraf<sup>52</sup>, M. P. J. Landon<sup>92</sup>, M. C. Lanfermann<sup>54</sup>, V. S. Lang<sup>46</sup>, J. C. Lange<sup>53</sup>, R. J. Langenberg<sup>36</sup>, A. J. Lankford<sup>171</sup>, F. Lanni<sup>29</sup>, K. Lantzsche<sup>24</sup>, A. Lanza<sup>70a</sup>, A. Lapertosa<sup>55a,55b</sup>, S. Laplace<sup>136</sup>, J. F. Laporte<sup>145</sup>, T. Lari<sup>68a</sup>, F. Lasagni Manghi<sup>23a,23b</sup>, M. Lassnig<sup>36</sup>, T. S. Lau<sup>63a</sup>, A. Laudrain<sup>132</sup>, A. Laurier<sup>34</sup>, M. Lavorgna<sup>69a,69b</sup>, M. Lazzaroni<sup>68a,68b</sup>, B. Le<sup>104</sup>, O. Le Dortz<sup>136</sup>, E. Le Guirrec<sup>101</sup>, M. LeBlanc<sup>7</sup>, T. LeCompte<sup>6</sup>, F. Ledroit-Guillon<sup>58</sup>, C. A. Lee<sup>29</sup>, G. R. Lee<sup>17</sup>, L. Lee<sup>59</sup>, S. C. Lee<sup>158</sup>, S. J. Lee<sup>34</sup>, B. Lefebvre<sup>168a</sup>, M. Lefebvre<sup>176</sup>, F. Legger<sup>114</sup>, C. Leggett<sup>18</sup>, K. Lehmann<sup>152</sup>, N. Lehmann<sup>182</sup>, G. Lehmann Miotto<sup>36</sup>, W. A. Leight<sup>46</sup>, A. Leisos<sup>162,v</sup>, M. A. L. Leite<sup>80d</sup>, R. Leitner<sup>143</sup>, D. Lellouch<sup>180,\*</sup>, K. J. C. Leney<sup>42</sup>, T. Lenz<sup>24</sup>, B. Lenzi<sup>36</sup>, R. Leone<sup>7</sup>, S. Leone<sup>71a</sup>, C. Leonidopoulos<sup>50</sup>, A. Leopold<sup>136</sup>, G. Lerner<sup>156</sup>, C. Leroy<sup>109</sup>, R. Les<sup>167</sup>, C. G. Lester<sup>32</sup>, M. Levchenko<sup>138</sup>, J. Levêque<sup>5</sup>, D. Levin<sup>105</sup>, L. J. Levinson<sup>180</sup>, D. J. Lewis<sup>21</sup>, B. Li<sup>15b</sup>, B. Li<sup>105</sup>, C.-Q. Li<sup>60a</sup>, F. Li<sup>60c</sup>, H. Li<sup>60a</sup>, H. Li<sup>60b</sup>, J. Li<sup>60c</sup>, K. Li<sup>153</sup>, L. Li<sup>60c</sup>, M. Li<sup>15a</sup>, Q. Li<sup>15a,15d</sup>, Q. Y. Li<sup>60a</sup>, S. Li<sup>60c,60d</sup>, X. Li<sup>46</sup>, Y. Li<sup>46</sup>, Z. Li<sup>60b</sup>, Z. Liang<sup>15a</sup>, B. Liberti<sup>73a</sup>, A. Liblong<sup>167</sup>, K. Lie<sup>63c</sup>, S. Liem<sup>120</sup>, C. Y. Lin<sup>32</sup>, K. Lin<sup>106</sup>, T. H. Lin<sup>99</sup>, R. A. Linck<sup>65</sup>, J. H. Lindon<sup>21</sup>, A. L. Lionti<sup>54</sup>, E. Lipeles<sup>137</sup>, A. Lipniacka<sup>17</sup>, M. Lisovsky<sup>61b</sup>, T. M. Liss<sup>173,as</sup>, A. Lister<sup>175</sup>, A. M. Litke<sup>146</sup>, J. D. Little<sup>8</sup>, B. Liu<sup>78,ab</sup>, B. L. Liu<sup>6</sup>, H. B. Liu<sup>29</sup>, H. Liu<sup>105</sup>, J. B. Liu<sup>60a</sup>, J. K. K. Liu<sup>135</sup>, K. Liu<sup>136</sup>, M. Liu<sup>60a</sup>, P. Liu<sup>18</sup>, Y. Liu<sup>15a,15d</sup>, Y. L. Liu<sup>105</sup>, Y. W. Liu<sup>60a</sup>,



M. Livan<sup>70a,70b</sup>, A. Lleres<sup>58</sup>, J. Llorente Merino<sup>15a</sup>, S. L. Lloyd<sup>92</sup>, C. Y. Lo<sup>63b</sup>, F. Lo Sterzo<sup>42</sup>, E. M. Lobodzinska<sup>46</sup>, P. Loch<sup>7</sup>, S. Loffredo<sup>73a,73b</sup>, T. Lohse<sup>19</sup>, K. Lohwasser<sup>149</sup>, M. Lokajicek<sup>141</sup>, J. D. Long<sup>173</sup>, R. E. Long<sup>89</sup>, L. Longo<sup>36</sup>, K. A. Looper<sup>126</sup>, J. A. Lopez<sup>147b</sup>, I. Lopez Paz<sup>100</sup>, A. Lopez Solis<sup>149</sup>, J. Lorenz<sup>114</sup>, N. Lorenzo Martinez<sup>5</sup>, M. Losada<sup>22</sup>, P. J. Lösel<sup>114</sup>, A. Lösle<sup>52</sup>, X. Lou<sup>46</sup>, X. Lou<sup>15a</sup>, A. Lounis<sup>132</sup>, J. Love<sup>6</sup>, P. A. Love<sup>89</sup>, J. J. Lozano Bahilo<sup>174</sup>, M. Lu<sup>60a</sup>, Y. J. Lu<sup>64</sup>, H. J. Lubatti<sup>148</sup>, C. Luci<sup>72a,72b</sup>, A. Lucotte<sup>58</sup>, C. Luedtke<sup>52</sup>, F. Luehring<sup>65</sup>, I. Luise<sup>136</sup>, L. Luminari<sup>72a</sup>, B. Lund-Jensen<sup>154</sup>, M. S. Lutz<sup>102</sup>, D. Lynn<sup>29</sup>, R. Lysak<sup>141</sup>, E. Lytken<sup>96</sup>, F. Lyu<sup>15a</sup>, V. Lyubushkin<sup>79</sup>, T. Lyubushkina<sup>79</sup>, H. Ma<sup>29</sup>, L. L. Ma<sup>60b</sup>, Y. Ma<sup>60b</sup>, G. Maccarrone<sup>51</sup>, A. Macchiolo<sup>115</sup>, C. M. Macdonald<sup>149</sup>, J. Machado Miguens<sup>137</sup>, D. Madaffari<sup>174</sup>, R. Madar<sup>38</sup>, W. F. Mader<sup>48</sup>, N. Madysa<sup>48</sup>, J. Maeda<sup>82</sup>, K. Maekawa<sup>163</sup>, S. Maeland<sup>17</sup>, T. Maeno<sup>29</sup>, M. Maerker<sup>48</sup>, A. S. Maevskiy<sup>113</sup>, V. Magerl<sup>52</sup>, N. Magini<sup>78</sup>, D. J. Mahon<sup>39</sup>, C. Maidantchik<sup>80b</sup>, T. Maier<sup>114</sup>, A. Maio<sup>140a,140b,140d</sup>, O. Majersky<sup>28a</sup>, S. Majewski<sup>131</sup>, Y. Makida<sup>81</sup>, N. Makovec<sup>132</sup>, B. Malaescu<sup>136</sup>, Pa. Malecki<sup>84</sup>, V. P. Maleev<sup>138</sup>, F. Malek<sup>58</sup>, U. Mallik<sup>77</sup>, D. Malon<sup>6</sup>, C. Malone<sup>32</sup>, S. Maltezos<sup>10</sup>, S. Malyukov<sup>36</sup>, J. Mamuzic<sup>174</sup>, G. Mancini<sup>51</sup>, I. Mandić<sup>91</sup>, L. Manhaes de Andrade Filho<sup>80a</sup>, I. M. Maniatis<sup>162</sup>, J. Manjarres Ramos<sup>48</sup>, K. H. Mankinen<sup>96</sup>, A. Mann<sup>114</sup>, A. Manousos<sup>76</sup>, B. Mansoulie<sup>145</sup>, I. Mantos<sup>162</sup>, S. Manzoni<sup>120</sup>, A. Marantis<sup>162</sup>, G. Marceca<sup>30</sup>, L. Marchese<sup>135</sup>, G. Marchiori<sup>136</sup>, M. Marcisovsky<sup>141</sup>, C. Marcon<sup>96</sup>, C. A. Marin Tobon<sup>36</sup>, M. Marjanovic<sup>38</sup>, F. Marroquim<sup>80b</sup>, Z. Marshall<sup>18</sup>, M.U.F. Martensson<sup>172</sup>, S. Marti-Garcia<sup>174</sup>, C. B. Martin<sup>126</sup>, T. A. Martin<sup>178</sup>, V. J. Martin<sup>50</sup>, B. Martin dit Latour<sup>17</sup>, L. Martinelli<sup>74a,74b</sup>, M. Martinez<sup>14,w</sup>, V. I. Martinez Outschoorn<sup>102</sup>, S. Martin-Haugh<sup>144</sup>, V. S. Martoiu<sup>27b</sup>, A. C. Martyniuk<sup>94</sup>, A. Marzin<sup>36</sup>, L. Masetti<sup>99</sup>, T. Mashimo<sup>163</sup>, R. Mashinistov<sup>110</sup>, J. Masik<sup>100</sup>, A. L. Maslennikov<sup>122a,122b</sup>, L. H. Mason<sup>104</sup>, L. Massa<sup>73a,73b</sup>, P. Massarotti<sup>69a,69b</sup>, P. Mastrandrea<sup>71a,71b</sup>, A. Mastroberardino<sup>41a,41b</sup>, T. Masubuchi<sup>163</sup>, A. Matic<sup>114</sup>, P. Mättig<sup>24</sup>, J. Maurer<sup>27b</sup>, B. Maček<sup>91</sup>, S. J. Maxfield<sup>90</sup>, D. A. Maximov<sup>122a,122b</sup>, R. Mazini<sup>158</sup>, I. Maznas<sup>162</sup>, S. M. Mazza<sup>146</sup>, S. P. Mc Kee<sup>105</sup>, T. G. McCarthy<sup>115</sup>, L. I. McClymont<sup>94</sup>, W. P. McCormack<sup>18</sup>, E. F. McDonald<sup>104</sup>, J. A. Mcfayden<sup>36</sup>, G. Mchedlidze<sup>53</sup>, M. A. McKay<sup>42</sup>, K. D. McLean<sup>176</sup>, S. J. McMahon<sup>144</sup>, P. C. McNamara<sup>104</sup>, C. J. McNicol<sup>178</sup>, R. A. McPherson<sup>176,ac</sup>, J. E. Mdhluli<sup>33c</sup>, Z. A. Meadows<sup>102</sup>, S. Meehan<sup>148</sup>, T. Megy<sup>52</sup>, S. Mehlhase<sup>114</sup>, A. Mehta<sup>90</sup>, T. Meideck<sup>58</sup>, B. Meirose<sup>43</sup>, D. Melini<sup>174</sup>, B. R. Mellado Garcia<sup>33c</sup>, J. D. Mellenthin<sup>53</sup>, M. Melo<sup>28a</sup>, F. Meloni<sup>46</sup>, A. Melzer<sup>24</sup>, S. B. Menary<sup>100</sup>, E. D. Mendes Gouveia<sup>140a,140e</sup>, L. Meng<sup>36</sup>, X. T. Meng<sup>105</sup>, S. Menke<sup>115</sup>, E. Meoni<sup>41a,41b</sup>, S. Mergelmeyer<sup>19</sup>, S. A. M. Merkt<sup>139</sup>, C. Merlassino<sup>20</sup>, P. Mermod<sup>54</sup>, L. Merola<sup>69a,69b</sup>, C. Meroni<sup>68a</sup>, O. Meshkov<sup>113,110</sup>, J. K. R. Meshreki<sup>151</sup>, A. Messina<sup>72a,72b</sup>, J. Metcalfe<sup>6</sup>, A. S. Mete<sup>171</sup>, C. Meyer<sup>65</sup>, J. Meyer<sup>160</sup>, J-P. Meyer<sup>145</sup>, H. Meyer Zu Theenhausen<sup>61a</sup>, F. Miano<sup>156</sup>, R. P. Middleton<sup>144</sup>, L. Mijović<sup>50</sup>, G. Mikenberg<sup>180</sup>, M. Mikestikova<sup>141</sup>, M. Mikuž<sup>91</sup>, H. Mildner<sup>149</sup>, M. Milesi<sup>104</sup>, A. Milic<sup>167</sup>, D. A. Millar<sup>92</sup>, D. W. Miller<sup>37</sup>, A. Milov<sup>180</sup>, D. A. Milstead<sup>45a,45b</sup>, R. A. Mina<sup>153,p</sup>, A. A. Minaenko<sup>123</sup>, M. Miñano Moya<sup>174</sup>, I. A. Minashvili<sup>159b</sup>, A. I. Mincer<sup>124</sup>, B. Mindur<sup>83a</sup>, M. Mineev<sup>79</sup>, Y. Minegishi<sup>163</sup>, Y. Ming<sup>181</sup>, L. M. Mir<sup>14</sup>, A. Mirto<sup>67a,67b</sup>, K. P. Mistry<sup>137</sup>, T. Mitani<sup>179</sup>, J. Mitrevski<sup>114</sup>, V. A. Mitsou<sup>174</sup>, M. Mittal<sup>60c</sup>, A. Miucci<sup>20</sup>, P. S. Miyagawa<sup>149</sup>, A. Mizukami<sup>81</sup>, J. U. Mjörnmark<sup>96</sup>, T. Mkrtchyan<sup>184</sup>, M. Mlynarikova<sup>143</sup>, T. Moa<sup>45a,45b</sup>, K. Mochizuki<sup>109</sup>, P. Mogg<sup>52</sup>, S. Mohapatra<sup>39</sup>, R. Moles-Valls<sup>24</sup>, M. C. Mondragon<sup>106</sup>, K. Mönig<sup>46</sup>, J. Monk<sup>40</sup>, E. Monnier<sup>101</sup>, A. Montalbano<sup>152</sup>, J. Montejo Berlingen<sup>36</sup>, M. Montella<sup>94</sup>, F. Monticelli<sup>88</sup>, S. Monzani<sup>68a</sup>, N. Morange<sup>132</sup>, D. Moreno<sup>22</sup>, M. Moreno Llácer<sup>36</sup>, P. Morettini<sup>55b</sup>, M. Morgenstern<sup>120</sup>, S. Morgenstern<sup>48</sup>, D. Mori<sup>152</sup>, M. Morii<sup>59</sup>, M. Morinaga<sup>179</sup>, V. Morisbak<sup>134</sup>, A. K. Morley<sup>36</sup>, G. Mornacchi<sup>36</sup>, A. P. Morris<sup>94</sup>, L. Morvaj<sup>155</sup>, P. Moschovakos<sup>36</sup>, B. Moser<sup>120</sup>, M. Mosidze<sup>159b</sup>, T. Moskalets<sup>145</sup>, H. J. Moss<sup>149</sup>, J. Moss<sup>31,m</sup>, K. Motohashi<sup>165</sup>, E. Mountricha<sup>36</sup>, E. J. W. Moyse<sup>102</sup>, S. Muanza<sup>101</sup>, J. Mueller<sup>139</sup>, R. S. P. Mueller<sup>114</sup>, D. Muenstermann<sup>89</sup>, G. A. Mullier<sup>96</sup>, J. L. Munoz Martinez<sup>14</sup>, F. J. Munoz Sanchez<sup>100</sup>, P. Murin<sup>28b</sup>, W. J. Murray<sup>178,144</sup>, A. Murrone<sup>68a,68b</sup>, M. Muškinja<sup>18</sup>, C. Mwewa<sup>33a</sup>, A. G. Myagkov<sup>123,an</sup>, J. Myers<sup>131</sup>, M. Myska<sup>142</sup>, B. P. Nachman<sup>18</sup>, O. Nackenhorst<sup>47</sup>, A. Nag Nag<sup>48</sup>, K. Nagai<sup>135</sup>, K. Nagano<sup>81</sup>, Y. Nagasaka<sup>62</sup>, M. Nagel<sup>52</sup>, E. Nagy<sup>101</sup>, A. M. Nairz<sup>36</sup>, Y. Nakahama<sup>117</sup>, K. Nakamura<sup>81</sup>, T. Nakamura<sup>163</sup>, I. Nakano<sup>127</sup>, H. Nanjo<sup>133</sup>, F. Napolitano<sup>61a</sup>, R. F. Naranjo Garcia<sup>46</sup>, R. Narayan<sup>11</sup>, D. I. Narrias Villar<sup>61a</sup>, I. Naryshkin<sup>138</sup>, T. Naumann<sup>46</sup>, G. Navarro<sup>22</sup>, H. A. Neal<sup>105,\*</sup>, P. Y. Nechaeva<sup>110</sup>, F. Nechansky<sup>46</sup>, T. J. Neep<sup>21</sup>, A. Negri<sup>70a,70b</sup>, M. Negrini<sup>23b</sup>, C. Nellist<sup>53</sup>, M. E. Nelson<sup>135</sup>, S. Nemecek<sup>141</sup>, P. Nemethy<sup>124</sup>, M. Nessi<sup>36,d</sup>, M. S. Neubauer<sup>173</sup>, M. Neumann<sup>182</sup>, P. R. Newman<sup>21</sup>, T. Y. Ng<sup>63c</sup>, Y. S. Ng<sup>19</sup>, Y. W. Y. Ng<sup>171</sup>, H. D. N. Nguyen<sup>101</sup>, T. Nguyen Manh<sup>109</sup>, E. Nibigira<sup>38</sup>, R. B. Nickerson<sup>135</sup>, R. Nicolaidou<sup>145</sup>, D. S. Nielsen<sup>40</sup>, J. Nielsen<sup>146</sup>, N. Nikiforou<sup>11</sup>, V. Nikolaenko<sup>123,an</sup>, I. Nikolic-Audit<sup>136</sup>, K. Nikolopoulos<sup>21</sup>, P. Nilsson<sup>29</sup>, H. R. Nindhito<sup>54</sup>, Y. Ninomiya<sup>81</sup>, A. Nisati<sup>72a</sup>, N. Nishu<sup>60c</sup>, R. Nisius<sup>115</sup>, I. Nitsche<sup>47</sup>, T. Nitta<sup>179</sup>, T. Nobe<sup>163</sup>, Y. Noguchi<sup>85</sup>, M. Nomachi<sup>133</sup>, I. Nomidis<sup>136</sup>, M. A. Nomura<sup>29</sup>, M. Nordberg<sup>36</sup>, N. Norjoharuddeen<sup>135</sup>, T. Novak<sup>91</sup>, O. Novgorodova<sup>48</sup>, R. Novotny<sup>142</sup>, L. Nozka<sup>130</sup>, K. Ntekas<sup>171</sup>, E. Nurse<sup>94</sup>, F. G. Oakham<sup>34,av</sup>, H. Oberlack<sup>115</sup>, J. Ocariz<sup>136</sup>, A. Ochi<sup>82</sup>, I. Ochoa<sup>39</sup>, J. P. Ochoa-Ricoux<sup>147a</sup>, K. O'Connor<sup>26</sup>, S. Oda<sup>87</sup>, S. Odaka<sup>81</sup>, S. Oerdek<sup>53</sup>, A. Ogrodnik<sup>83a</sup>, A. Oh<sup>100</sup>, S. H. Oh<sup>49</sup>, C. C. Ohm<sup>154</sup>, H. Oide<sup>55a,55b</sup>, M. L. Ojeda<sup>167</sup>, H. Okawa<sup>169</sup>, Y. Okazaki<sup>85</sup>, Y. Okumura<sup>163</sup>, T. Okuyama<sup>81</sup>, A. Olariu<sup>27b</sup>, L. F. Oleiro Seabra<sup>140a</sup>, S. A. Olivares Pino<sup>147a</sup>, D. Oliveira Damazio<sup>29</sup>, J. L. Oliver<sup>1</sup>, M. J. R. Olsson<sup>171</sup>, A. Olszewski<sup>84</sup>, J. Olszowska<sup>84</sup>, D. C. O'Neil<sup>152</sup>, A. Onofre<sup>140a,140e</sup>, K. Onogi<sup>117</sup>,



P. U. E. Onyisi<sup>11</sup>, H. Oppen<sup>134</sup>, M. J. Oreglia<sup>37</sup>, G. E. Orellana<sup>88</sup>, Y. Oren<sup>161</sup>, D. Orestano<sup>74a,74b</sup>, N. Orlando<sup>14</sup>, R. S. Orr<sup>167</sup>, V. O'Shea<sup>57</sup>, R. Ospanov<sup>60a</sup>, G. Otero y Garzon<sup>30</sup>, H. Otono<sup>87</sup>, M. Ouchrif<sup>35d</sup>, F. Ould-Saada<sup>134</sup>, A. Ouraou<sup>145</sup>, Q. Ouyang<sup>15a</sup>, M. Owen<sup>57</sup>, R. E. Owen<sup>21</sup>, V. E. Ozcan<sup>12c</sup>, N. Ozturk<sup>8</sup>, J. Pacalt<sup>130</sup>, H. A. Pacey<sup>32</sup>, K. Pachal<sup>49</sup>, A. Pacheco Pages<sup>14</sup>, C. Padilla Aranda<sup>14</sup>, S. Pagan Griso<sup>18</sup>, M. Paganini<sup>183</sup>, G. Palacino<sup>65</sup>, S. Palazzo<sup>50</sup>, S. Palestini<sup>36</sup>, M. Palka<sup>83b</sup>, D. Pallin<sup>38</sup>, I. Panagoulas<sup>10</sup>, C. E. Pandini<sup>36</sup>, J. G. Panduro Vazquez<sup>93</sup>, P. Pani<sup>46</sup>, G. Panizzo<sup>66a,66c</sup>, L. Paolozzi<sup>54</sup>, C. Papadatos<sup>109</sup>, K. Papageorgiou<sup>9,h</sup>, A. Paramonov<sup>6</sup>, D. Paredes Hernandez<sup>63b</sup>, S. R. Paredes Saenz<sup>135</sup>, B. Parida<sup>166</sup>, T. H. Park<sup>167</sup>, A. J. Parker<sup>89</sup>, M. A. Parker<sup>32</sup>, F. Parodi<sup>55a,55b</sup>, E. W. P. Parrish<sup>121</sup>, J. A. Parsons<sup>39</sup>, U. Parzefall<sup>52</sup>, L. Pascual Dominguez<sup>136</sup>, V. R. Pascuzzi<sup>167</sup>, J. M. P. Pasner<sup>146</sup>, E. Pasqualucci<sup>72a</sup>, S. Passaggio<sup>55b</sup>, F. Pastore<sup>93</sup>, P. Pasuwan<sup>45a,45b</sup>, S. Pataria<sup>99</sup>, J. R. Pater<sup>100</sup>, A. Pathak<sup>181</sup>, T. Pauly<sup>36</sup>, B. Pearson<sup>115</sup>, M. Pedersen<sup>134</sup>, L. Pedraza Diaz<sup>119</sup>, R. Pedro<sup>140a</sup>, T. Peiffer<sup>53</sup>, S. V. Peleganchuk<sup>122a,122b</sup>, O. Penc<sup>141</sup>, H. Peng<sup>60a</sup>, B. S. Peralva<sup>80a</sup>, M. M. Perego<sup>132</sup>, A. P. Pereira Peixoto<sup>140a</sup>, D. V. Perepelitsa<sup>29</sup>, F. Peri<sup>19</sup>, L. Perini<sup>68a,68b</sup>, H. Pernegger<sup>36</sup>, S. Perrella<sup>69a,69b</sup>, K. Peters<sup>46</sup>, R. F. Y. Peters<sup>100</sup>, B. A. Petersen<sup>36</sup>, T. C. Petersen<sup>40</sup>, E. Petit<sup>101</sup>, A. Petridis<sup>1</sup>, C. Petridou<sup>162</sup>, P. Petroff<sup>132</sup>, M. Petrov<sup>135</sup>, F. Petrucci<sup>74a,74b</sup>, M. Pettee<sup>183</sup>, N. E. Pettersson<sup>102</sup>, K. Petukhova<sup>143</sup>, A. Peyaud<sup>145</sup>, R. Pezoa<sup>147b</sup>, L. Pezzotti<sup>70a,70b</sup>, T. Pham<sup>104</sup>, F. H. Phillips<sup>106</sup>, P. W. Phillips<sup>144</sup>, M. W. Phipps<sup>173</sup>, G. Piacquadio<sup>155</sup>, E. Pianori<sup>18</sup>, A. Picazio<sup>102</sup>, R. H. Pickles<sup>100</sup>, R. Piegai<sup>30</sup>, D. Pietreanu<sup>27b</sup>, J. E. Pilcher<sup>37</sup>, A. D. Pilkington<sup>100</sup>, M. Pinamonti<sup>73a,73b</sup>, J. L. Pinfold<sup>3</sup>, M. Pitt<sup>180</sup>, L. Pizzimento<sup>73a,73b</sup>, M.-A. Pleier<sup>29</sup>, V. Pleskot<sup>143</sup>, E. Plotnikova<sup>79</sup>, D. Pluth<sup>78</sup>, P. Podberezko<sup>122a,122b</sup>, R. Poettgen<sup>96</sup>, R. Poggi<sup>54</sup>, L. Poggioli<sup>132</sup>, I. Pogrebnyak<sup>106</sup>, D. Pohl<sup>24</sup>, I. Pokharel<sup>53</sup>, G. Polesello<sup>70a</sup>, A. Poley<sup>18</sup>, A. Policicchio<sup>72a,72b</sup>, R. Polifka<sup>143</sup>, A. Polini<sup>23b</sup>, C. S. Pollard<sup>46</sup>, V. Polychronakos<sup>29</sup>, D. Ponomarenko<sup>112</sup>, L. Pontecorvo<sup>36</sup>, S. Popa<sup>27a</sup>, G. A. Popeneciu<sup>27d</sup>, D. M. Portillo Quintero<sup>58</sup>, S. Pospisil<sup>142</sup>, K. Potamianos<sup>46</sup>, I. N. Potrap<sup>79</sup>, C. J. Potter<sup>32</sup>, H. Potti<sup>11</sup>, T. Poulsen<sup>96</sup>, J. Poveda<sup>36</sup>, T. D. Powell<sup>149</sup>, G. Pownall<sup>46</sup>, M. E. Pozo Astigarraga<sup>36</sup>, P. Pralavorio<sup>101</sup>, S. Prell<sup>78</sup>, D. Price<sup>100</sup>, M. Primavera<sup>67a</sup>, S. Prince<sup>103</sup>, M. L. Proffitt<sup>148</sup>, N. Proklova<sup>112</sup>, K. Prokofiev<sup>63c</sup>, F. Prokoshin<sup>147b</sup>, S. Protopopescu<sup>29</sup>, J. Proudfoot<sup>6</sup>, M. Przybycien<sup>83a</sup>, A. Puri<sup>173</sup>, P. Puzo<sup>132</sup>, J. Qian<sup>105</sup>, Y. Qin<sup>100</sup>, A. Quadt<sup>53</sup>, M. Queitsch-Maitland<sup>46</sup>, A. Qureshi<sup>1</sup>, P. Rados<sup>104</sup>, F. Ragusa<sup>68a,68b</sup>, G. Rahal<sup>97</sup>, J. A. Raine<sup>54</sup>, S. Rajagopalan<sup>29</sup>, A. Ramirez Morales<sup>92</sup>, K. Ran<sup>15a,15d</sup>, T. Rashid<sup>132</sup>, S. Raspopov<sup>5</sup>, M. G. Ratti<sup>68a,68b</sup>, D. M. Rauch<sup>46</sup>, F. Rauscher<sup>114</sup>, S. Rave<sup>99</sup>, B. Ravina<sup>149</sup>, I. Ravinovich<sup>180</sup>, J. H. Rawling<sup>100</sup>, M. Raymond<sup>36</sup>, A. L. Read<sup>134</sup>, N. P. Readioff<sup>58</sup>, M. Reale<sup>67a,67b</sup>, D. M. Rebuzzi<sup>70a,70b</sup>, A. Redelbach<sup>177</sup>, G. Redlinger<sup>29</sup>, K. Reeves<sup>43</sup>, L. Rehnisch<sup>19</sup>, J. Reichert<sup>137</sup>, D. Reikher<sup>161</sup>, A. Reiss<sup>99</sup>, A. Rej<sup>151</sup>, C. Rembser<sup>36</sup>, M. Renda<sup>27b</sup>, M. Rescigno<sup>72a</sup>, S. Resconi<sup>68a</sup>, E. D. Resseguie<sup>137</sup>, S. Rettie<sup>175</sup>, E. Reynolds<sup>21</sup>, O. L. Rezanova<sup>122a,122b</sup>, P. Reznicek<sup>143</sup>, E. Ricci<sup>75a,75b</sup>, R. Richter<sup>115</sup>, S. Richter<sup>46</sup>, E. Richter-Was<sup>83b</sup>, O. Ricken<sup>24</sup>, M. Ridel<sup>136</sup>, P. Rieck<sup>115</sup>, C. J. Riegel<sup>182</sup>, O. Rifki<sup>46</sup>, M. Rijssenbeek<sup>155</sup>, A. Rimoldi<sup>70a,70b</sup>, M. Rimoldi<sup>20</sup>, L. Rinaldi<sup>23b</sup>, G. Ripellino<sup>154</sup>, B. Ristic<sup>89</sup>, E. Ritsch<sup>36</sup>, I. Riu<sup>14</sup>, J. C. Rivera Vergara<sup>147a</sup>, F. Rizatdinova<sup>129</sup>, E. Rizvi<sup>92</sup>, C. Rizzi<sup>36</sup>, R. T. Roberts<sup>100</sup>, S. H. Robertson<sup>103,ac</sup>, M. Robin<sup>46</sup>, D. Robinson<sup>32</sup>, J. E. M. Robinson<sup>46</sup>, A. Robson<sup>57</sup>, E. Rocco<sup>99</sup>, C. Roda<sup>71a,71b</sup>, S. Rodriguez Bosca<sup>174</sup>, A. Rodriguez Perez<sup>14</sup>, D. Rodriguez Rodriguez<sup>174</sup>, A. M. Rodriguez Vera<sup>168b</sup>, S. Roe<sup>36</sup>, O. Røhne<sup>134</sup>, R. Röhrig<sup>115</sup>, C. P. A. Roland<sup>65</sup>, J. Roloff<sup>59</sup>, A. Romaniouk<sup>112</sup>, M. Romano<sup>23a,23b</sup>, N. Rempotis<sup>90</sup>, M. Ronzani<sup>124</sup>, L. Roos<sup>136</sup>, S. Rosati<sup>72a</sup>, K. Rosbach<sup>52</sup>, N.-A. Rosien<sup>53</sup>, G. Rosin<sup>102</sup>, B. J. Rosser<sup>137</sup>, E. Rossi<sup>46</sup>, E. Rossi<sup>74a,74b</sup>, E. Rossi<sup>69a,69b</sup>, L. P. Rossi<sup>55b</sup>, L. Rossini<sup>68a,68b</sup>, R. Rosten<sup>14</sup>, M. Rotaru<sup>27b</sup>, J. Rothberg<sup>148</sup>, D. Rousseau<sup>132</sup>, G. Rovelli<sup>70a,70b</sup>, D. Roy<sup>33c</sup>, A. Rozanov<sup>101</sup>, Y. Rozen<sup>160</sup>, X. Ruan<sup>33c</sup>, F. Rubbo<sup>153</sup>, F. Rühr<sup>52</sup>, A. Ruiz-Martinez<sup>174</sup>, A. Rummler<sup>36</sup>, Z. Rurikova<sup>52</sup>, N. A. Rusakovich<sup>79</sup>, H. L. Russell<sup>103</sup>, L. Rustige<sup>38,47</sup>, J. P. Rutherford<sup>7</sup>, E. M. Rüttinger<sup>46,j</sup>, Y. F. Ryabov<sup>138</sup>, M. Rybar<sup>39</sup>, G. Rybkin<sup>132</sup>, A. Ryzhov<sup>123</sup>, G. F. Rzehorz<sup>53</sup>, P. Sabatini<sup>53</sup>, G. Sabato<sup>120</sup>, S. Sacerdoti<sup>132</sup>, H.F.-W. Sadrozinski<sup>146</sup>, R. Sadykov<sup>79</sup>, F. Safai Tehrani<sup>72a</sup>, B. Safarzadeh Samani<sup>156</sup>, P. Saha<sup>121</sup>, S. Saha<sup>103</sup>, M. Sahinsoy<sup>61a</sup>, A. Sahu<sup>182</sup>, M. Saimpert<sup>46</sup>, M. Saito<sup>163</sup>, T. Saito<sup>163</sup>, H. Sakamoto<sup>163</sup>, A. Sakharov<sup>124,am</sup>, D. Salamani<sup>54</sup>, G. Salamanna<sup>74a,74b</sup>, J. E. Salazar Loyola<sup>147b</sup>, P. H. Sales De Bruin<sup>172</sup>, D. Salihagic<sup>115,\*</sup>, A. Salnikov<sup>153</sup>, J. Salt<sup>174</sup>, D. Salvatore<sup>41a,41b</sup>, F. Salvatore<sup>156</sup>, A. Salvucci<sup>63a,63b,63c</sup>, A. Salzburger<sup>36</sup>, J. Samarati<sup>36</sup>, D. Sammel<sup>52</sup>, D. Sampsonidis<sup>162</sup>, D. Sampsonidou<sup>162</sup>, J. Sánchez<sup>174</sup>, A. Sanchez Pineda<sup>66a,66c</sup>, H. Sandaker<sup>134</sup>, C. O. Sander<sup>46</sup>, I. G. Sanderswood<sup>89</sup>, M. Sandhoff<sup>182</sup>, C. Sandoval<sup>22</sup>, D. P. C. Sankey<sup>144</sup>, M. Sannino<sup>55a,55b</sup>, Y. Sano<sup>117</sup>, A. Sansoni<sup>51</sup>, C. Santoni<sup>38</sup>, H. Santos<sup>140a,140b</sup>, S. N. Santpur<sup>18</sup>, A. Santra<sup>174</sup>, A. Saponov<sup>79</sup>, J. G. Saraiva<sup>140a,140d</sup>, O. Sasaki<sup>81</sup>, K. Sato<sup>169</sup>, E. Sauvan<sup>5</sup>, P. Savard<sup>167,av</sup>, N. Savic<sup>115</sup>, R. Sawada<sup>163</sup>, C. Sawyer<sup>144</sup>, L. Sawyer<sup>95,ak</sup>, C. Sbarra<sup>23b</sup>, A. Sbrizzi<sup>23a</sup>, T. Scanlon<sup>94</sup>, J. Schaarschmidt<sup>148</sup>, P. Schacht<sup>115</sup>, B. M. Schachtner<sup>114</sup>, D. Schaefer<sup>37</sup>, L. Schaefer<sup>137</sup>, J. Schaeffer<sup>99</sup>, S. Schaepe<sup>36</sup>, U. Schäfer<sup>99</sup>, A. C. Schaffer<sup>132</sup>, D. Schaile<sup>114</sup>, R. D. Schamberger<sup>155</sup>, N. Scharmberg<sup>100</sup>, V. A. Schegelsky<sup>138</sup>, D. Scheirich<sup>143</sup>, F. Schenck<sup>19</sup>, M. Schernau<sup>171</sup>, C. Schiavi<sup>55a,55b</sup>, S. Schier<sup>146</sup>, L. K. Schildgen<sup>24</sup>, Z. M. Schillaci<sup>26</sup>, E. J. Schioppa<sup>36</sup>, M. Schioppa<sup>41a,41b</sup>, K. E. Schleicher<sup>52</sup>, S. Schlenker<sup>36</sup>, K. R. Schmidt-Sommerfeld<sup>115</sup>, K. Schmieden<sup>36</sup>, C. Schmitt<sup>99</sup>, S. Schmitt<sup>46</sup>, S. Schmitt<sup>99</sup>, J. C. Schmoeckel<sup>46</sup>, U. Schnoor<sup>52</sup>, L. Schoeffel<sup>145</sup>, A. Schoening<sup>61b</sup>, E. Schopf<sup>135</sup>, M. Schott<sup>99</sup>, J. F. P. Schouwenberg<sup>119</sup>, J. Schovancova<sup>36</sup>, S. Schramm<sup>54</sup>, F. Schroeder<sup>182</sup>, A. Schulte<sup>99</sup>, H.-C. Schultz-Coulon<sup>61a</sup>,

M. Schumacher<sup>52</sup>, B. A. Schumm<sup>146</sup>, Ph. Schune<sup>145</sup>, A. Schwartzman<sup>153</sup>, T. A. Schwarz<sup>105</sup>, Ph. Schwemling<sup>145</sup>, R. Schwienhorst<sup>106</sup>, A. Sciandra<sup>146</sup>, G. Sciolla<sup>26</sup>, M. Scodeggio<sup>46</sup>, M. Scornajenghi<sup>41a,41b</sup>, F. Scuri<sup>71a</sup>, F. Scutti<sup>104</sup>, L. M. Scyboz<sup>115</sup>, C. D. Sebastiani<sup>72a,72b</sup>, P. Seema<sup>19</sup>, S. C. Seidel<sup>118</sup>, A. Seiden<sup>146</sup>, T. Seiss<sup>37</sup>, J. M. Seixas<sup>80b</sup>, G. Sekhniaidze<sup>69a</sup>, K. Sekhon<sup>105</sup>, S. J. Sekula<sup>42</sup>, N. Semprini-Cesari<sup>23a,23b</sup>, S. Sen<sup>49</sup>, S. Senkin<sup>38</sup>, C. Serfon<sup>76</sup>, L. Serin<sup>132</sup>, L. Serkin<sup>66a,66b</sup>, M. Sessa<sup>60a</sup>, H. Severini<sup>128</sup>, F. Sforza<sup>170</sup>, A. Sfyrta<sup>54</sup>, E. Shabalina<sup>53</sup>, J. D. Shahinian<sup>146</sup>, N. W. Shaikh<sup>45a,45b</sup>, D. Shaked Renous<sup>180</sup>, L. Y. Shan<sup>15a</sup>, R. Shang<sup>173</sup>, J. T. Shank<sup>25</sup>, M. Shapiro<sup>18</sup>, A. S. Sharma<sup>1</sup>, A. Sharma<sup>135</sup>, P. B. Shatalov<sup>111</sup>, K. Shaw<sup>156</sup>, S. M. Shaw<sup>100</sup>, A. Shcherbakova<sup>138</sup>, Y. Shen<sup>128</sup>, N. Sherafati<sup>34</sup>, A. D. Sherman<sup>25</sup>, P. Sherwood<sup>94</sup>, L. Shi<sup>158,ar</sup>, S. Shimizu<sup>81</sup>, C. O. Shimmin<sup>183</sup>, Y. Shimogama<sup>179</sup>, M. Shimojima<sup>116</sup>, I. P. J. Shipsey<sup>135</sup>, S. Shirabe<sup>87</sup>, M. Shiyakova<sup>79,z</sup>, J. Shlomi<sup>180</sup>, A. Shmeleva<sup>110</sup>, M. J. Shochet<sup>37</sup>, S. Shojaii<sup>104</sup>, D. R. Shope<sup>128</sup>, S. Shrestha<sup>126</sup>, E. Shulga<sup>180</sup>, P. Sicho<sup>141</sup>, A. M. Sickles<sup>173</sup>, P. E. Sidebo<sup>154</sup>, E. Sideras Haddad<sup>33c</sup>, O. Sidiropoulou<sup>36</sup>, A. Sidoti<sup>23a,23b</sup>, F. Siegert<sup>48</sup>, Dj. Sijacki<sup>16</sup>, M. Silva Jr.<sup>181</sup>, M. V. Silva Oliveira<sup>80a</sup>, S. B. Silverstein<sup>45a</sup>, S. Simion<sup>132</sup>, E. Simioni<sup>99</sup>, R. Simoniello<sup>99</sup>, P. Sinervo<sup>167</sup>, N. B. Sinev<sup>131</sup>, M. Sioli<sup>23a,23b</sup>, I. Siral<sup>105</sup>, S. Yu. Sivoklov<sup>113</sup>, J. Sjölin<sup>45a,45b</sup>, E. Skorda<sup>96</sup>, P. Skubic<sup>128</sup>, M. Slawinska<sup>84</sup>, K. Sliwa<sup>170</sup>, R. Slovak<sup>143</sup>, V. Smakhtin<sup>180</sup>, B. H. Smart<sup>144</sup>, J. Smiesko<sup>28a</sup>, N. Smirnov<sup>112</sup>, S. Yu. Smirnov<sup>112</sup>, Y. Smirnov<sup>112</sup>, L. N. Smirnova<sup>113,s</sup>, O. Smirnova<sup>96</sup>, J. W. Smith<sup>53</sup>, M. Smizanska<sup>89</sup>, K. Smolek<sup>142</sup>, A. Smykiewicz<sup>84</sup>, A. A. Snesarev<sup>110</sup>, H. L. Snoek<sup>120</sup>, I. M. Snyder<sup>131</sup>, S. Snyder<sup>29</sup>, R. Sobie<sup>176,ac</sup>, A. M. Soffa<sup>171</sup>, A. Soffer<sup>161</sup>, A. Søgaard<sup>50</sup>, F. Sohns<sup>53</sup>, C. A. Solans Sanchez<sup>36</sup>, E. Yu. Soldatov<sup>112</sup>, U. Soldevila<sup>174</sup>, A. A. Solodkov<sup>123</sup>, A. Soloshenko<sup>79</sup>, O. V. Solovyanov<sup>123</sup>, V. Solovyev<sup>138</sup>, P. Sommer<sup>149</sup>, H. Son<sup>170</sup>, W. Song<sup>144</sup>, W. Y. Song<sup>168b</sup>, A. Sopczak<sup>142</sup>, F. Sopkova<sup>28b</sup>, C. L. Sotiropoulou<sup>71a,71b</sup>, S. Sottocornola<sup>70a,70b</sup>, R. Soualah<sup>66a,66c,g</sup>, A. M. Soukharev<sup>122a,122b</sup>, D. South<sup>46</sup>, S. Spagnolo<sup>67a,67b</sup>, M. Spalla<sup>115</sup>, M. Spangenberg<sup>178</sup>, F. Spanò<sup>93</sup>, D. Sperlich<sup>52</sup>, T. M. Spieker<sup>61a</sup>, R. Spighi<sup>23b</sup>, G. Spigo<sup>36</sup>, M. Spina<sup>156</sup>, D. P. Spiteri<sup>57</sup>, M. Spousta<sup>143</sup>, A. Stabile<sup>68a,68b</sup>, B. L. Stamas<sup>121</sup>, R. Stamen<sup>61a</sup>, M. Stamenkovic<sup>120</sup>, E. Stanecka<sup>84</sup>, R. W. Stanek<sup>6</sup>, B. Stanislaus<sup>135</sup>, M. M. Stanitzki<sup>46</sup>, M. Stankaityte<sup>135</sup>, B. Stapf<sup>120</sup>, E. A. Starchenko<sup>123</sup>, G. H. Stark<sup>146</sup>, J. Stark<sup>58</sup>, S. H. Stark<sup>40</sup>, P. Staroba<sup>141</sup>, P. Starovoitov<sup>61a</sup>, S. Stärz<sup>103</sup>, R. Staszewski<sup>84</sup>, G. Stavropoulos<sup>44</sup>, M. Stegler<sup>46</sup>, P. Steinberg<sup>29</sup>, A. L. Steinhebel<sup>131</sup>, B. Stelzer<sup>152</sup>, H. J. Stelzer<sup>139</sup>, O. Stelzer-Chilton<sup>168a</sup>, H. Stenzel<sup>56</sup>, T. J. Stevenson<sup>156</sup>, G. A. Stewart<sup>36</sup>, M. C. Stockton<sup>36</sup>, G. Stoicea<sup>27b</sup>, M. Stolarski<sup>140a</sup>, P. Stolte<sup>53</sup>, S. Stonjek<sup>115</sup>, A. Straessner<sup>48</sup>, J. Strandberg<sup>154</sup>, S. Strandberg<sup>45a,45b</sup>, M. Strauss<sup>128</sup>, P. Strizeneć<sup>28b</sup>, R. Ströhmer<sup>177</sup>, D. M. Strom<sup>131</sup>, R. Stroynowski<sup>42</sup>, A. Strubig<sup>50</sup>, S. A. Stucci<sup>29</sup>, B. Stugu<sup>17</sup>, J. Stupak<sup>128</sup>, N. A. Styles<sup>46</sup>, D. Su<sup>153</sup>, S. Suchek<sup>61a</sup>, Y. Sugaya<sup>133</sup>, V. V. Sulin<sup>110</sup>, M. J. Sullivan<sup>90</sup>, D. M. S. Sultan<sup>54</sup>, S. Sultansoy<sup>4c</sup>, T. Sumida<sup>85</sup>, S. Sun<sup>105</sup>, X. Sun<sup>3</sup>, K. Suruliz<sup>156</sup>, C. J. E. Suster<sup>157</sup>, M. R. Sutton<sup>156</sup>, S. Suzuki<sup>81</sup>, M. Svatos<sup>141</sup>, M. Swiatlowski<sup>37</sup>, S. P. Swift<sup>2</sup>, T. Swirski<sup>177</sup>, A. Sydorenko<sup>99</sup>, I. Sykora<sup>28a</sup>, M. Sykora<sup>143</sup>, T. Sykora<sup>143</sup>, D. Ta<sup>99</sup>, K. Tackmann<sup>46,x</sup>, J. Taenzer<sup>161</sup>, A. Taffard<sup>171</sup>, R. Tafiout<sup>168a</sup>, E. Tahirovic<sup>92</sup>, H. Takai<sup>29</sup>, R. Takashima<sup>86</sup>, K. Takeda<sup>82</sup>, T. Takeshita<sup>150</sup>, E. P. Takeva<sup>50</sup>, Y. Takubo<sup>81</sup>, M. Talby<sup>101</sup>, A. A. Talyshev<sup>122a,122b</sup>, N. M. Tamir<sup>161</sup>, J. Tanaka<sup>163</sup>, M. Tanaka<sup>165</sup>, R. Tanaka<sup>132</sup>, B. B. Tannenwald<sup>126</sup>, S. Tapia Araya<sup>173</sup>, S. Tapprogge<sup>99</sup>, A. Tarek Abouelfadl Mohamed<sup>136</sup>, S. Tarem<sup>160</sup>, G. Tarna<sup>27b,c</sup>, G. F. Tartarelli<sup>68a</sup>, P. Tas<sup>143</sup>, M. Tasevsky<sup>141</sup>, T. Tashiro<sup>85</sup>, E. Tassi<sup>41a,41b</sup>, A. Tavares Delgado<sup>140a,140b</sup>, Y. Tayalati<sup>35e</sup>, A. J. Taylor<sup>50</sup>, G. N. Taylor<sup>104</sup>, W. Taylor<sup>168b</sup>, A. S. Tee<sup>89</sup>, R. Teixeira De Lima<sup>153</sup>, P. Teixeira-Dias<sup>93</sup>, H. Ten Kate<sup>36</sup>, J. J. Teoh<sup>120</sup>, S. Terada<sup>81</sup>, K. Terashi<sup>163</sup>, J. Terron<sup>98</sup>, S. Terzo<sup>14</sup>, M. Testa<sup>51</sup>, R. J. Teuscher<sup>167,ac</sup>, S. J. Thais<sup>183</sup>, T. Theveneaux-Pelzer<sup>46</sup>, F. Thiele<sup>40</sup>, D. W. Thomas<sup>93</sup>, J. O. Thomas<sup>42</sup>, J. P. Thomas<sup>21</sup>, A. S. Thompson<sup>57</sup>, P. D. Thompson<sup>21</sup>, L. A. Thomsen<sup>183</sup>, E. Thomson<sup>137</sup>, Y. Tian<sup>39</sup>, R. E. Ticse Torres<sup>53</sup>, V. O. Tikhomirov<sup>110,ao</sup>, Yu. A. Tikhonov<sup>122a,122b</sup>, S. Timoshenko<sup>112</sup>, P. Tipton<sup>183</sup>, S. Tisserant<sup>101</sup>, K. Todome<sup>23a,23b</sup>, S. Todorova-Nova<sup>5</sup>, S. Todt<sup>48</sup>, J. Tojo<sup>87</sup>, S. Tokár<sup>28a</sup>, K. Tokushuku<sup>81</sup>, E. Tolley<sup>126</sup>, K. G. Tomiwa<sup>33c</sup>, M. Tomoto<sup>117</sup>, L. Tompkins<sup>153,p</sup>, K. Toms<sup>118</sup>, B. Tong<sup>59</sup>, P. Tornambe<sup>102</sup>, E. Torrence<sup>131</sup>, H. Torres<sup>48</sup>, E. Torró Pastor<sup>148</sup>, C. Tosciro<sup>135</sup>, J. Toth<sup>101,aa</sup>, D. R. Tovey<sup>149</sup>, C. J. Treado<sup>124</sup>, T. Trefzger<sup>177</sup>, F. Tresoldi<sup>156</sup>, A. Tricoli<sup>29</sup>, I. M. Trigger<sup>168a</sup>, S. Trincz-Duvoid<sup>136</sup>, W. Trischuk<sup>167</sup>, B. Trocme<sup>58</sup>, A. Trofymov<sup>132</sup>, C. Troncon<sup>68a</sup>, M. Trovatelli<sup>176</sup>, F. Trovato<sup>156</sup>, L. Truong<sup>33b</sup>, M. Trzebinski<sup>84</sup>, A. Trzupek<sup>84</sup>, F. Tsai<sup>46</sup>, J.C.-L. Tseng<sup>135</sup>, P. V. Tsiarashka<sup>107,ai</sup>, A. Tsirigotis<sup>162</sup>, N. Tsirintanis<sup>9</sup>, V. Tsiskaridze<sup>155</sup>, E. G. Tskhadadze<sup>159a</sup>, M. Tsopoulou<sup>162</sup>, I. I. Tsukerman<sup>111</sup>, V. Tsulaia<sup>18</sup>, S. Tsuno<sup>81</sup>, D. Tsybychev<sup>155</sup>, Y. Tu<sup>63b</sup>, A. Tudorache<sup>27b</sup>, V. Tudorache<sup>27b</sup>, T. T. Tulbure<sup>27a</sup>, A. N. Tuna<sup>59</sup>, S. Turchikhin<sup>79</sup>, D. Turgeman<sup>180</sup>, I. Turk Cakir<sup>4b,t</sup>, R. J. Turner<sup>21</sup>, R. T. Turra<sup>68a</sup>, P. M. Tuts<sup>39</sup>, S. Tzamarias<sup>162</sup>, E. Tzovara<sup>99</sup>, G. Ucchielli<sup>47</sup>, K. Uchida<sup>163</sup>, I. Ueda<sup>81</sup>, M. Ughetto<sup>45a,45b</sup>, F. Ukegawa<sup>169</sup>, G. Unal<sup>36</sup>, A. Undrus<sup>29</sup>, G. Unel<sup>171</sup>, F. C. Ungaro<sup>104</sup>, Y. Unno<sup>81</sup>, K. Uno<sup>163</sup>, J. Urban<sup>28b</sup>, P. Urquijo<sup>104</sup>, G. Usai<sup>8</sup>, J. Usui<sup>81</sup>, L. Vacavant<sup>101</sup>, V. Vacek<sup>142</sup>, B. Vachon<sup>103</sup>, K. O. H. Vadla<sup>134</sup>, A. Vaidya<sup>94</sup>, C. Valderanis<sup>114</sup>, E. Valdes Santurio<sup>45a,45b</sup>, M. Valente<sup>54</sup>, S. Valentini<sup>23a,23b</sup>, A. Valero<sup>174</sup>, L. Valéry<sup>46</sup>, R. A. Vallance<sup>21</sup>, A. Vallier<sup>36</sup>, J. A. Valls Ferrer<sup>174</sup>, T. R. Van Daalen<sup>14</sup>, P. Van Gemmeren<sup>6</sup>, I. Van Vulpen<sup>120</sup>, M. Vanadia<sup>73a,73b</sup>, W. Vandelli<sup>36</sup>, A. Vaniachine<sup>166</sup>, D. Vannicola<sup>72a,72b</sup>, R. Vari<sup>72a</sup>, E. W. Varnes<sup>7</sup>, C. Varni<sup>55a,55b</sup>, T. Varol<sup>42</sup>, D. Varouchas<sup>132</sup>, K. E. Varvell<sup>157</sup>, M. E. Vasile<sup>27b</sup>, G. A. Vasquez<sup>176</sup>, J. G. Vasquez<sup>183</sup>, F. Vazeille<sup>38</sup>, D. Vazquez Furelos<sup>14</sup>, T. Vazquez Schroeder<sup>36</sup>, J. Veatch<sup>53</sup>, V. Vecchio<sup>74a,74b</sup>, M. J. Veen<sup>120</sup>, L. M. Veloce<sup>167</sup>,

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